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The Design of Compliant Seating for Children with Severe Whole Body Extensor Spasms

Adlam, Tim

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The Design of Compliant Seating for Children with Severe Whole Body Extensor Spasms

Timothy Adlam

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Summary

Children with cerebral palsy and powerful whole body extensor spasms find sitting in a rigid seat uncomfortable and sometimes painful due to the large forces they apply to their constraints. They are usually unable to speak and communication is difficult. The spasms affect every aspect of their lives.

This thesis describes the genesis of a new functional dynamic seat for children with severe whole body extensor spasms, and the novel method used to design it. This novel seat technology is known as 'Whole Body Dynamic Seating'. The thesis describes the clinical need this seat addresses, and the design and technology context in which this research takes place. The user evaluation, observation, measurement, analysis and reasoning that led to a successful seat design are described in detail.

Children with cerebral palsy sometimes have whole body spasms that mean they cannot be seated in conventional static seating that positions a child in a fixed posture. For this research the children were classified as functioning at Chailey Sitting Ability Level 1 and Gross Motor Functional Classification System Level V. Such children spend much of their time being held by a person, or lying on a mat, bed or pad. This results in difficulty with social engagement and physical functioning, particularly in school. This research created a seat that such children could sit in, providing a comfortable and functional seat for use in a home or school classroom environment.

This seat was designed with the direct and essential involvement of disabled children, their parents, therapists, teachers and carers. The work is part of a larger programme of research into seating and support technology that will enhance a child's ability to gain functional movement and communication skills that can be employed to enable the child's free self expression and social participation.

The research investigated means of supporting children with whole body extensor spasms through a progressive iterative method utilizing direct user evaluation of a series of prototypes incrementing in complexity and fidelity towards a fully functional physical seat.

An iterative method was used to design, build and evaluate three dynamic seats. This method incorporated two new approaches to prototyping developed for the research programme in response to difficulties encountered in designing dynamic systems for children with highly complex neuromotor disability. Soft and Semi-soft prototyping and evaluation methods provided essential feedback on dynamic seating concepts that guided proposed solutions, without requiring costly and time-consuming manufacture. Video was used to create a record of the children's movements and responses for subsequent analysis. Instrumentation was built into the seats to enable direct objective measurement of the reaction forces and seat movement caused by extensor spasms.

This thesis presents several unique features created through this research programme:

1. Independent and virtually hinged anatomical dynamic thigh supports;
2. Independent anatomical dynamic foot supports;
3. A virtually hinged dynamic back support;
4. An anatomical dynamic head support concept.

The final Whole Body Dynamic Seat was child-centred in its functionality and aesthetic design, and was favourably commented upon by parents, children and school staff.

Use of the new dynamic seating by three children (including one from a previous work programme) showed that children with severe whole body extensor spasms can be seated comfortably. The children also demonstrated gains in physical and social function as a result of using the dynamic seats.

The two fully independent dynamic seats made advances in comfort over static seating for children with whole body extensor spasms. One of the children especially liked the seat and resisted being put back into his usual seating. An adult with severe cerebral palsy and extensor spasms evaluated a dynamic foot support concept and reported very significant reductions in spasticity and pain, and gains in physical function.

The Whole Body Dynamic Seats showed gains in postural symmetry and in hand and head function over the usual static seats when used by the children with spasms. These gains were reported by staff during long term evaluations and measured specifically during the final evaluation. Two children learned to control the movement of seats in which they were sat, and were able to control their posture and use that control to carry out functions such as switch pressing. Such learning through the use of dynamic seating by children with severe dystonic cerebral palsy and whole body extensor spasms has not previously been documented.

The seats did not just affect the children - school staff were affected too. School staff working around the children in the dynamic seats were observed to be more inclusive towards the children, and to expect more interaction from them. The ability of the children to move altered staff expectations of their ability to participate and communicate.

This new seating has improved the quality of life of the children that use it. Future implementation of this technology in commercially produced seating offers the possibility of similar gains to many more severely disabled children who are currently less comfortable and less functional than they need to be.

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Project Participants

Bath Institute of Medical Engineering (BIME): Tim Adlam and Prof. Roger Orpwood. Tel. 01225 824103. BIME, Wolfson Centre, Royal United Hospital, Bath.

Great Ormond Street Hospital: Alison Wisbeach, Helen Alger and Eleanor Johnson; Dept. Occupational Therapy, Great Ormond Street Hospital, Great Ormond Street, London.

University of Bath Department of Mechanical Engineering: Prof. Anthony Miles; Tel. 01225 386368; Dept. Mechanical Engineering, University of Bath, Claverton Down, Bath.

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Background

Chapter 1

Introduction

"Assistive technology is not for fixing problems; it exists to enable the free expression of capability and personhood. Even a humble bottom wiper exists to enable a person to be free to visit, travel and work. This research is about enabling a child to be a child, to be a person, take risks, learn from mistakes, gain skills, express creativity, express emotions, enjoy experience, nurture relationships and become a complete and fully realised person. The journey continues."

The Author

Sitting

Sitting is something that most people are able to do when they are tired, need to work, or for many other reasons. It is a posture we adopt for rest and for function. I am sitting as I write this introduction because the posture stabilises my trunk and enables my hands to work efficiently; it positions me in front of the table at a convenient height to type on my laptop; and it enables me to rest my legs and back as I work.

Some children cannot sit on a conventional seat or even a specialist seat designed to provide postural support for a disabled child without discomfort or even pain. This is because they have a movement disorder such as Dystonic Cerebral Palsy[14] that causes them to experience frequent involuntary spasms of the extensor muscles throughout their whole body.

Extensor spasms cause the extensor muscles to contract powerfully and involuntarily; creating different movements such as:

- The spine and neck arching backwards;
- The legs extending at the hips, and the knees and ankles straightening;
- The legs rotating inwards at the hip joints;
- The arms extending backwards at the shoulders, the elbows straightening and the wrists arching forwards.

- The head turning to one side.

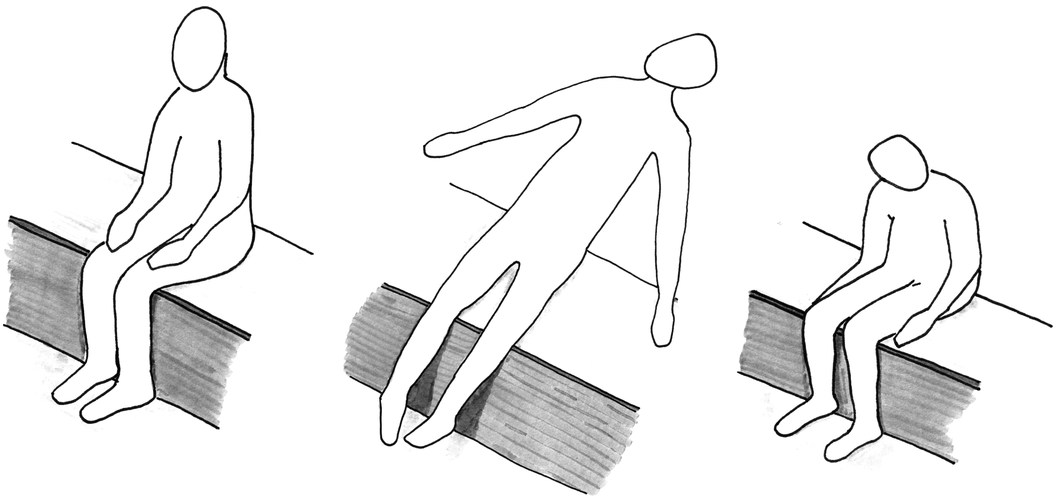

Figure 1-1: Extensor spasm movements: This sketch shows three children. The first child *(LEFT)* is sitting in a stable upright position and is not disabled. The second child *(CENTRE)* is experiencing a whole body extensor spasm. The third child *(RIGHT)* is sitting in a slumped position typical of a child with low tone. Many children with extensor spasm have low tone when they are not experiencing spasms. This means that they not only need seating that can accommodate powerful spasms, but also seating that can provide sufficient support in between spasms. The extensor spasm movements are powerful, involuntary, and can occur as frequently as every two seconds, with a short period of relaxation or flexor spasm in between.

These movements, shown in Figure 1-1, occur simultaneously. Their frequency is highly variable. They can occur as frequently as every two seconds if the child is distressed or excited, or occur only every few minutes when the child is more relaxed and calm. Some children may pass an hour or more without a spasm. However, they often come quickly and with little warning, particularly if the child is startled. Some research into dynamic seating has induced spasms on demand using loud noises to startle the child[2].

The overall effect of the spasms is to cause the body to straighten, whatever its position or orientation. Because of the frequent high intensity exercise that these children experience, they are very strong – much stronger than a non-disabled child of their own age. An practical example of this strength arose during an evaluation of a seat by one of the children recruited to this work. The boy was age six years at the time. His spasms were causing his knees to move together (this is known as hip adduction). The project engineer attempted to hold his knees in the desired position slightly apart from one another (abducted) while the project occupational therapist adjusted the seat. This action by the engineer required considerable strength and could not be maintained for very long. It is possible that extensor spasms may be strong enough to fracture the child's bones[15]. Living with frequent spasms every day is disruptive to family and school life, places severe demands on the child's body, and is painful. The spasms dominate a child's life and affect every aspect of it including eating, playing, sleeping, travelling and learning.

Extensor spasms are painful and distressing for the child, and, aside from providing suitable support and therapy, and an appropriate environment for the child; there is little that can be done medically to prevent them, short of major interventions to reduce tone in the child's muscles. Medical interventions include:

- **Baclofen:** A muscle relaxant drug related to the neurotransmitter gamma-aminobutyric acid - GABA[16, 17];
- **Botulinum toxin:** A drug that is injected into affected muscles, completely or partially paralysing them for several months[18];
- **Selective dorsal rhizotomy:** The irreversible surgical severing of selected efferent nerves that stimulate muscle activity[19];
- **Stem cell therapy:** Injections of stem cells into the affected regions of the brain may be beneficial and offer a chance of some recovery from the effects of damage to the motor regions of the brain[20].

Medical interventions such as these can reduce discomfort resulting from spasticity and spasms, leading to improved quality of life. They work by removing the ability of the body to activate certain muscle groups. In children with low tone, as many are who have extensor spasms, reducing muscle activity further between spasms is not necessarily desirable and may negatively impact on function[21].

Thus the primary aim of this work was to:

- Design a generalised compliant seat that enables children with whole body extensor spasms to sit comfortably;

An approach to seating was taken where compliance in the seat structure was used to modify the child's experience of seating, and to blunt the spasm response by allowing the seat to yield as a spasm occurs. This approach was derived from previous observation by the occupational therapy team of the way that parents and carers hold children and how they adapt their positioning of the child when a spasm occurs. NOTE: The terms 'compliant' and 'dynamic' are used interchangeably in the literature to describe a seat that is able to move with the occupant's movements.

The research presented spans two projects: The first was the clinical referral of an individual child to BIME from Great Ormond Street Hospital, and the second was a research project funded by Action Medical Research to design a seat that would be comfortable for children with whole body extensor spasms who are unseatable in a rigid seat. Both the referral and the research project were collaborations between a clinical occupational therapy team from Great Ormond Street and an engineering team from BIME, working closely with the children's parents, therapists and teachers.

1.1 Research Overview

The objective of this research was to design a comfortable seat suitable for every-day use by children with whole body extensor spasms, often due to dystonic cerebral palsy. The research reported in this thesis occurred in the context of two projects. The first was a referral from Great Ormond Street Hospital Department of Occupational Therapy for the design of a seat for an individual child; and the second was a research project to design a generic seat suitable for many children with whole body spasms. Both of these projects resulted in novel seating and demonstrated that some children with whole body extensor spasms can be seated successfully in dynamic seating.

1.1.1 Project 1: Design of a seat for an individual child with dystonic cerebral palsy and whole body extensor spasms

The first project was for the design of a seat for a specific child under a referral from Great Ormond Street Hospital for Children. The completed dynamic seat (described in Chapter 6) was delivered to the child in early 2008. The seat employed a sprung and linked dynamic back and footrest mechanism, and sat the child on a 'saddle' seat with his legs apart (abducted). It was designed using iterative methods and substantial user evaluation. The seat was successful for this child in that it was comfortable and significantly reduced the restraint forces on his body. He was able to sit in the seat for extended periods of time, unlike any previous seat he had been supplied with, and used it every day at home. This project provided the foundation and starting point for the research into a generic seat which followed.

1.1.2 Project 2: Design of a generic seat for children with whole body extensor spasms

The second project was to design a generic chair suitable for many children with whole body extensor spasms. This project ran in three phases:

Phase 1: Design of a prototype exploratory seat The first phase of the project was intended to be the characterisation of extensor spasms using an instrumented test seat, however it proved not to be possible to seat the recruited children in the initially designed and built seat for sufficient time to achieve this. Phase one was restructured to be a design, build and evaluate cycle for a seat that was based on the Project One seat briefly described above. During this time one child was recruited to the project that met the inclusion criteria defined in Section 3.4. The design of this seat is described in Chapter 7 and its evaluation in Chapter 8.

Evaluation methods: Soft and Semi-soft prototyping New cost and time efficient prototyping and evaluation methods were developed as a response to:

1. The need to reduce the risks to the project associated with abandoning the initial plan and embarking on a new untried concept;
2. Difficulty in quickly evaluating complex dynamic seating concepts without the time consuming design and construction of complex prototypes.

These methods are described in Chapter 4.

Phase 2: Iterative Seat Design and Evaluation With the failure of the first prototype to provide a suitable platform for further evaluation of dynamic seating for children with whole body extensor spasms; and the results of an informative and unconventional evaluation session at the child's home; a decision was made to design the seat to a new concept where the child's back, hips and knees were able to move independently, stabilising the head and shoulders, and with hip movement being favoured over back movement.

Having recruited an additional child, Phase Two incorporated three design/build/evaluate iterations of increasing fidelity to the new fully independent dynamic seat concept. The design iterations comprising this work are described in Section 9.3 and Chapter 10; and the evaluations in Chapters 9 and 11.

Phase 3: Generic seat design and data analysis Following the modest success of the independent seat prototype evaluation in Phase Two, a second independent seat was designed that built upon the findings from the evaluation of the first independent seat; and advanced the design towards it being a useable every-day seat. A longer term evaluation was carried out, and the results were analysed. The design work is described in Chapter 14 and the evaluation in Chapter 15.

Discussion The results of all the evaluations are discussed in the context of the literature in Chapter 17.

Further work This work has led to further research proposals being developed, which are described in Chapter 18.

Chapter 2

Literature Review

This chapter describes an ongoing review of literature relevant to this research. It covers a short section of quantification of extensor spasms, and then longer sections on existing dynamic seating designs and postural interventions for the support of function in children with cerebral palsy. This is an under researched area of work, with a paucity of literature available on both extensor spasms and dynamic seat design. For this reason the literature search was continued as the research developed, and the review covers the few available papers individually and in depth.

2.1 Cerebral Palsy and Extensor Spasms

Extensor spasms are one of many potential symptoms of cerebral palsy. They can affect the whole body and cause the extensor muscles to contract simultaneously. The extensor muscles are those that, for example, cause the arms and legs to straighten, the fingers to extend, the spine and neck to arch backwards. The spasms are not under the voluntary control of the child. They can be triggered by the child being startled by a sudden noise; by anxiety, stress or excitement; or by the posture of the child or by other causes not immediately obvious.

Within the seating literature they are often characterised as an 'extensor thrust', due to the effect they have on a child sitting in a rigid chair. When a spasm occurs, the powerful associated hip extension thrusts the child's pelvis forwards and upwards in the chair, against or under the lap strap. The spasm also extends the knees, arms and neck. The effect overall is that the child attempts to bridge across the front of the seat base and the back of the backrest or head support if present, and increases pressure against the lap-strap. This causes abrasion and pressure damage to the skin, and matting of the hair on the head. The spasm may last for a fraction of a second or even minutes, and can be very painful.

2.1.1 Quantification of Forces Associated with Episodic Full-Body Extensor Spasticity in Children, Brown et al, 2001[1]

This paper is unusual in that it presents quantitative data describing the strength of whole body extensor spasms, though the data presented in the paper cited is less complete than the data presented in the slides that accompanied the corresponding conference presentation[9].

The paper describes an experiment that measured the forces and torques applied to an instrumented wheelchair backrest by children experiencing whole body extensor spasms. Forces were measured using a pressure profiling mat that also indicates the location of the pressures applied to the backrest. The data from this experiment is shown in Figure 2-1.

Original Data from Brown, D (2001)								Calculated data		
Subject	**Age**	**Diagnosis**	**Peak Total Force (lbs.)**	**Peak Torque (ft-lbs)**	**Peak COPh (in)**	**Peak COPv (in)**	**Maximum Area of Contact (in2)**	***Peak Total Force (N)***	***Peak COPv (mm)***	***Peak Torque (Nm)***
								=(D6/2.2)*9.8	***=F6*25.4***	***=I6*(J6/1000)***
Subject 1	15	Glutaric Aciduria	133.1	119.8	13.9	19.7	231.3	*593.5*	*500.38*	*297.0*
Subject 2	7	Cerebral Palsy	158.6	89.4	13.4	8	132	*707.2*	*203.2*	*143.7*
Subject 3	11	Cerebral Palsy	85.4	73.2	18.6	12.4	133.2	*380.8*	*314.96*	*119.9*
Subject 4	13	Lesch-Nyhan	236.1	181.6	16.7	15.8	198.6	*1052.8*	*401.32*	*422.5*
Subject S	11	Cerebral Palsy	142.4	133.7	12.9	17.4	203.4	*635.0*	*441.96*	*280.6*
Subject 6	8	Cerebral Palsy	94.9	93.5	18.2	18.5	88.4	*423.2*	*469.9*	*198.8*
Subject 7	16	Cerebral Palsy	187.9	227	17.3	15.9	197.4	*837.9*	*403.86*	*338.4*
Subiect 8	11	Cerebral Palsy	34.4	28.2	15.7	10.6	131.9	*153.4*	*269.24*	*41.3*
Subject 9	9	Cerebral Palsy	58.8	40.9	12.3	13.2	141.7	*262.2*	*335.28*	*87.9*
Subject 10	12	Cerebral Palsy	29.1	13.9	13.4	15.4	127.2	*129.8*	*391.16*	*50.8*
Subject 11	9	Cerebral Palsy	75.6	75.1	16.5	14.5	142.8	*337.1*	*368.3*	*124.2*
Subject 12	9	Cerebral Palsy	47.3	44.7	18.4	14.3	132	*210.9*	*363.22*	*76.6*
Subject 13	12	Cerebral Palsy	60.8	398	11.4	12.5	142.9	*271.1*	*317.5*	*86.1*
Subject 14	10	Cerebral Palsy	77.1	106.4	12.1	17.1	99.3	*343.8*	*434.34*	*149.3*
Subiect 15	7	Lesch-Nyhan	45.9	31.7	14.8	13.5	93.2	*204.7*	*342.9*	*70.2*
Subject 16	14	Cerebral Palsy	142.9	106.7	13.9	13.5	235.1	*637.2*	*342.9*	*218.5*
Subject 17	11	Cerebral Palsy	18.9	16.5	18.6	15.9	109	*84.3*	*403.86*	*34.0*
Subject 18	5	Cerebral Palsy	31.3	25.9	18.6	15.3	41.2	*139.6*	*388.62*	*54.2*

COPh = width across centre of pressure | COPv = Vertical distance to centre of pressure from seat base

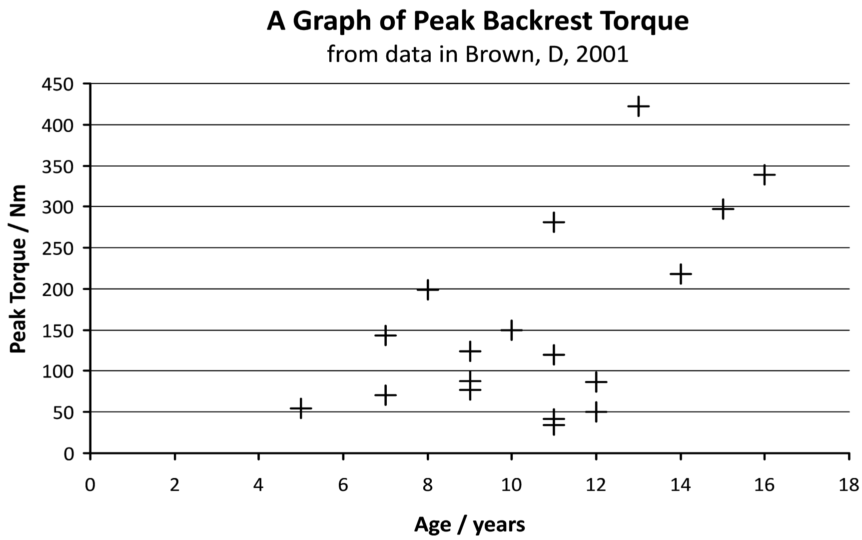

Figure 2-1: Measured force and pressure data from the Brown presentation[9], together with calculated SI values that were used to guide the design of the first prototype seat. The ages and diagnoses of the children were taken from the Brown RESNA presentation slides as this data was not present in the proceedings paper. This is an original chart produced from Brown's data[1, 9].

Discussion This experiment was conducted to provide preliminary data prior to further work in this area. The data shows that there is wide variation in the torques applied to seating by children with extensor spasms, with torques in this population varying between 13.9ft-lbs and 227ft-lbs (16.3Nm and 267Nm). The authors do not draw any firm conclusions about the nature of the spasms beyond the presentation of the data except that they are variable and that further work is needed to characterise them. They do indicate that the auditory stimulus used to trigger spasms was not always successful, and speculate that this may have been because the noise was not loud enough or that the sudden loud noises are not effective as a trigger in some children.

The paper does not give the ages of the children studied. In the presentation slides used when the paper was presented at RESNA, the ages of the subjects are given. This paper contains the only quantitative data on extensor spasms that has been found in the literature, aside from some data in a paper by Cimolin et al[2] that evaluates the R82 X-Panda dynamic seat.

The Brown paper gives hip extension torques applied by the children about an axis level with seat base. This paper provides a useful indication of the range of torques that children might apply to *any* seat.

2.2 Existing Approaches to Extensor Spasm Management

NOTE: Due to the paucity of papers published in this area of research, this section of the literature review examines papers individually rather than reviewing thematically across larger numbers of papers.

Specialised seating is provided to many children with cerebral palsy to manage their posture; to ensure that function is maintained for as long as possible; and to prevent skeletal deformity as much as possible. Cerebral palsy does not affect the skeleton directly, but rather the abnormal muscle tone and abnormal posture it induces apply long term forces to the skeleton that result in remodelling of the bones and the formation of contractures and other soft tissue problems. These problems are addressed through various therapeutic interventions including physiotherapy and the use of postural management systems, including seating. This section reviews existing dynamic seating systems designed for children with extensor spasms.

2.2.1 3D-Quantitative evaluation of a rigid seating system and dynamic seating system using 3D movement analysis in individuals with dystonic tetraparesis, Veronica Cimolin et al, 2009[2, 3]

This paper describes an evaluation of the R82 X-Panda dynamic seat by ten children with cerebral palsy, assessed at Level V on the Gross Motor Function Classification Scale (GMFCS)[22]. The seat was evaluated in its locked and dynamic configurations, and the movement of the children in the seat were analysed using 3D motion capture technology. Several parameters were defined for measurement:

Head

- EIH index (End and Initial position of Head)
- ROMH index (Range Of Motion of Head)

Trunk

- EIT index (End and Initial position of Trunk)
- ROMT index (Range Of Motion of Trunk)

Upper limb

- ROMW (Range of Motion of the upper limb measured as the difference between start and end position during a spasm) An 'Average Jerk Index' was calculated for this parameter that represented the smoothness of the motion, where Average Jerk

$$= \frac{1}{T} \int_{T}^{0} \left(\frac{d^3x}{dt^3}\right)^2 + \left(\frac{d^3y}{dt^3}\right)^2 + \left(\frac{d^3z}{dt^3}\right)^3 \,\mathrm{d}t$$

These parameters were measured using an electro-optical motion capture system. Spasms were induced by startling the participants with a sudden noise.

Head movement

In the head movements, some changes occurred in the head position (EIH) between the beginning and end of the movement, but there was no significant difference between the two configurations.

The head range of motion (ROMH) was significantly larger in the dynamic configuration.

Trunk movement

Analysis of the EIT index data showed that the dynamic configuration of the seat allowed the trunk to rotate backwards, and then returned it to its original position. Positioning was maintained. The range of motion data (ROMT) showed that the range of movement was larger with the dynamic back active.

There was more downward vertical truncal movement in the static configuration than in the dynamic configuration. This was thought to be due to the participant slipping forwards and down the backrest during spasms.

Upper limb movement

Analysis of the upper limb movement showed that there was more movement of the upper limbs during spasms in both x and y directions. Less movement was initiated in the dynamic configuration.

The Jerk index was lower in the dynamic configuration compared with the static configuration, indicating smoother limb movement when the dynamic back was unlocked. It is possible that these results indicate improved control of the limbs with the dynamic back operating.

Backrest forces

The most interesting results in this study were from the pressure sensor. The dynamic back substantially reduced peak forces (not torques) on the backrest resulting in a reduction of mean force from 78N to 34N. This is a substantial decrease and is likely to indicate a significant increase in comfort for the child. Headrest forces were not significantly different.

Discussion

This paper describes a thorough quantitative evaluation of the X-Panda seat and shows that it has an impact on the child's movement beyond that of movement made possible by the seat mechanism. The seat positively impacts on the child's response to seating by reducing forces and enabling the child's movements to be smoother.

2.2.2 A Dynamic Seating System for Children with Cerebral Palsy, Michael Hahn et al, 2009[4]

This paper describes a commercially available seat (Rock Active) that has been assessed for its impact on the child measured using various functional scales. The aim of the research as stated in the paper was to:

“determine the initial effects of using a dynamic seating system as a therapeutic intervention in children with cerebral palsy.”

The researchers assessed the effectiveness of the ‘Rock Active’ chair that is manufactured in the United States by Kids Up, Inc, Belgrade, MT. It is very similar to the German InterCo Aktivline chair. Both of these chairs have a dynamic function that allows the occupant to extend at the hips and knees. This function is similar to the extension function implemented in the first assessment chair designed for the BIME work. The Rock Active chair was not known about when the BIME chair was designed as the Hahn paper was not published until the BIME work was underway. The Rock Active mechanism differs from the linked BIME seat in that during a spasm it allows the seat base to tilt and the knees to extend, while maintaining the backrest angle. These mechanism differences result in the following functional differences:

1. It does not allow asymmetric movement of the hips (though asymmetric movement of the knees is possible);
2. It maintains eye gaze direction during spasm, but does not maintain eye gaze height.
3. Its mechanism is more compact than the BIME design, and requires less space to operate.
4. It uses the user’s weight to return the seat to a normal sitting position.

Details of the spring/damping characteristics employed are not known.

The Hahn evaluation of the Rock Active chair focusses on functional outcomes following use of the chair by an initial cohort of sixteen children that was reduced to twelve. Of the twelve children that participated in the study, eight were in the experimental group using dynamic seating and four were in the control group using static seating. The children were assessed using the following outcome measures:

1. Active and passive range of motion (ROM);
2. Muscle spasticity was measure with the Modified Ashworth Scale (MAS);
3. The Gross Motor Function Measure (GMFM-66) was used to assess the patient’s ability to perform tasks such as lying/rolling, Sitting, crawl/kneel, standing and walk/run/jog.
4. The Paediatric Evaluation of Disability Inventory (PEDI) was used to assess the caregivers impression of the patients’ ability to perform daily living tasks in the categories of self care, mobility and social function.

The paper concluded that there was not a significant increase (p=0.05) in joint range of motion. Muscle spasticity decreased significantly over time in both groups, though there was not a significant group effect. There was not a significant group effect in either the GMFM-66 or PEDI measures. The small sample size reduced the statistical power of the study, however qualitative conclusions were still drawn:

- Hip and knee range of motion increased more in the dynamic group than in the static group.
- Muscle spasticity tended towards the mid range of the Modified Ashworth Scale. This was thought to be because of a training effect on children with low tone caused by the provision of a low resistance to movement against which the children in the dynamic seat used their muscles.
- The Gross Motor Function Measure (GMFM) scores showed an improvement for the experimental group in the standing and walk/jog/run categories.
- The most significant improvement in the experimental group was in the social category of the PEDI measure. Many of the parents reported that their children began interacting with peers, caregivers and siblings once they began to be comfortable with the new chair.

The paper concludes by stating:

> *"In conclusion, the dynamic system did not show any negative effects, but rather showed improvement in each measure. A general trend in the data suggests that use of dynamic seating will be of use to children with neuromuscular dysfunction. Further analysis of individual outcomes may yield more clinically significant findings."*
>
> Page 29, Paragraph 2

Discussion The Hahn study is one of a few evaluations of a dynamic seating system with disabled participants. It assesses a dynamic seat with whole body movement, though not with independent movement. The GMFM-66 and PEDI measures used with the Hahn study, coupled with the small sample size did not lead to many statistically significant results (see above). However some observations were made that suggest dynamic seating can improve function in physical and social domains. Most of the children who participated in the Hahn study were less disabled than those that participated in this work, so some of the gains (GMFM walk/jog/run for example) were unlikely to be reproduced in the BIME work. It is likely therefore, that the BIME seat, like the Rock Active seat, will have wider application to less disabled children, as well as being of benefit to the severely disabled whole body spasm group that fit the inclusion criteria. This important point suggests that future work should examine the usefulness of the BIME dynamic seat to less disabled children.

Hahn makes particular reference to qualitative gains in communication in the experimental group. The PEDI results showed greater improvements in the experimental group in the areas of Self Care and Social Function. Additionally, parents and carers also reported:

> *"... their child began interacting more with siblings, peers, and adult caregivers once they became familiar with the new dynamic system"*
>
> [4]Pages 28,29

This observation does not carry any statistical power, but it should be noted. Dynamic seating may positively affect communication and social interaction as well as physical functioning.

The possible lack of sensitivity in this study suggests that future work at this scale should use small n or n=1 methods; or that a much larger study is designed, with its concomitant challenges in recruitment and the high cost of seat construction or purchase. It would have been helpful to see individual trajectories in this study, and also an analysis stratified by initial GMFCS score.

2.2.3 The Development of a Novel Adaptive Seating System for Children with Neuromuscular Disorders, Telfer et al, 2009[5]

This paper is a brief technical note describing a novel dynamic backrest. Since this is a short note, rather than write a paraphrase, its text is reproduced verbatim and in full below:

> *"Adaptive seating has been defined as the customized prescription and application of sitting support devices based on therapeutic principles. It is recognized that for children with neuromuscular disorders that result in poor postural control, a comfortable adaptive seating system that provides them with the support needed to maintain a sitting position can be essential for raising their overall level of well being. These systems are also used to try and prevent or to slow the progression of skeletal deformities. However, problems with current adaptive seating systems do exist. After extensive research into these problems we developed a novel adaptive seating system which aims to improve on current designs. It includes a number of innovative features including:*
>
> - *Active dynamic supports: The backrest and headrest are mounted on gas springs, allowing them to move in order to accommodate the users task induced movement or abnormal muscle tone. The forces applied to and the position of the supports are monitored and used to control motors attached to the gas springs. This means that the user can, when required, be returned to their original position in a controlled but still dynamic manner. The 'floating' nature of these supports, especially the backrest, is also intended to allow for some growth of the user.*[This paragraph is not clear, but no further details are given. It is possible that the article is deliberately opaque to protect intellectual property.]
> - *Novel backrest shape: In an attempt to positively influence abnormal hip extensor tone, the users trunk is given a predominantly lateral rather than posterior type of support. Preliminary results suggest that this approach could have some beneficial effects in terms of reducing abnormal hip extensor tone.*
> - *Multi-planar tilting seat base: Tilting of the base in the sagittal and coronal planes can be actuated manually or pre-programmed to do so automatically at set intervals. This aims to improve user comfort and prevent the development of pressure sores and could also be used to accommodate deformities such as pelvic obliquities.*
>
> *Through these features the novel system has the potential to provide improved comfort, support and functionality for the users and to reduce the burden place on those who care for them."*

Discussion This technical note briefly describes the features of a novel system similar in its concept to the seat being designed for the BIME work. As with the Hahn study[4] and the Rock Active chair described there, this work is not aimed at children who are disabled with the severity of the population being addressed.

It introduces several novel concepts, not least the mainly lateral backrest supports, the multiplanar tilting base, and the actively controlled backrest springs.

2.2.4 Development Of Dynamic Seating System For High Tone Extensor Thrust, Patrangenaru, 2006[6]

This thesis describes the design of a dynamic or compliant seat with the objective of reducing the loads on a chair by accommodating extensor thrust through a compliant and sprung mechanism in the backrest and footrest of the chair. The author built a mathematical model of the chair and its occupant, and used this to construct a virtual model in WorkingModel2D (2D dynamic simulation software). This model, which was reduced through the application of constraints to a single degree of freedom (hip extension angle) was used to explore seat configuration parameters and to establish an initial design of seat. The mathematical model was validated experimentally by a healthy volunteer who was asked to perform certain movements simulating an extensor thrust.

The author also commissioned a survey of stakeholders in seating to form a basis for designing a seat. After the conclusions, the thesis presents the draft results of a user study conducted using focus groups and questionnaires. The study was carried out by R. L. Grubbs at the Georgia Institute of Technology based Rehabilitation Engineering Research Centre for Wheeled Mobility. The study addressed the following areas:

Participants

Who participated in the study? The study participants were therapists, young adult wheelchair users, parents and vendors. Eleven out of twenty three of the participants were therapists. One was a wheelchair user. It is not known what severity of disability the young adults associated with this survey experienced, though the differentiation between upper and lower body thrusts later in the survey suggests that most of the children associated with the survey were less disabled than the two children that were participants in this research and experienced whole body spasms at a rate higher than the ten / hour suggested as an average by the survey participants.

What experience did they have of specialized seating? Most had average or above average experience of specialist seating. It was not known what experience they had of dynamic seating. It is not likely that many of them used dynamic seating.

Extensor thrusts

How do thrusts travel through the body? Most survey participants believed that extensor thrusts originate in a variety of parts of the body; and recognised that there were emotional, physical and environmental triggers for thrusts.

How are purposeful thrusts used? It was recognised by all the participants that specialist seating users make functional use of extensor thrusts. Functions identified by many of the participants included:

1. Assist with transfers;
2. Change position in wheelchair;
3. Reach for objects (Rank 2);
4. Access switches (Rank 1);
5. Raise head;
6. Communicate;
7. Drive wheelchair.

The wheelchair user in the survey identified all these functions. No other functions were identified.

How do purposeful and involuntary thrusts differ? It was believed that purposeful thrusts could be distinguished from involuntary thrusts because they were slower and lasted longer.

How does the seating system react to user thrust? They also believed that a dynamic seat should react differently to a voluntary thrust versus a spasm, yielding to a spasm, but providing increased resistance to a purposeful movement so that the user has a stable structure to push against.

Adjustability and assembly

What assembly and adjustability features are desired? Several features were identified by the group as being useful or essential:

1. The seat should be be removable from its base, or fold for transport.
2. It should be infinitely adjustable with one tool or no tools.
3. They preferred the seat to be adjustable for growth rather than employ a ‘growth kit’.
4. The seat should work with standard backrest components to reduce costs.

Dynamic features

What are the dynamic features of the seating system? The participants wanted the dynamic seat to be able to be dynamic some of the time, but also incorporate the ability to be configured as a static seat in multiple positions.

What advanced design methods [active control features] are employed? The participants wanted the seat to be active, sensing and responding to the occupant.

What features do stakeholders want in "rate of return"? They wanted adjustable and variable return rates and resistance to movement, depending on whether a movement was involuntary or voluntary.

With the model and survey complete, the author went on to design a seat with the following aims:

- Improving occupant comfort and safety;
- Improving system durability.

The author stated that:

> *"A highly–adjustable dynamic seating system is proposed to address many of the needs of those affected by high–tone extensor thrusts. These needs are identified by making use of the findings from the study in the previous chapter [the model development], as well as input from caregivers of children with cerebral palsy. This seating system is designed as a stand-alone solution for some of the affected individuals, as well as a springboard for further research in this area"*
>
> [6], Page 37

To this end, he designed a dynamic seat with a dynamic seat back, force and torque measurement. The seat also incorporated a 'rigidizer' that could be electronically energised to lock the seat back hinge mechanism. The seat was mounted on a frame with wheels that could be moved from room to room, though not without lifting half the weight of the whole assembly.

The seat frame geometry was conventional in that it consisted of three planes — footrest, seat platform and backrest — which were hinged. The footrest was hinged to the seat platform at a point behind the knee and in line with the seat platform. The backrest was hinged at a point in line with the backrest and above the seat platform. The seat frame could be adjusted in four ways:

1. Tibial length — the distance from the seat platform to the foot rest could be adjusted for length.
2. Pivot height — the height of the seat back pivot above the seat base could be adjusted.
3. Pivot position — the position of the backrest pivot could be adjusted about an axis below the pivot and in line with the backrest.
4. Backrest height — the height of the backrest could be adjusted, depending on the spinal length of the occupant.

The thesis proposed some alternative designs that were more complex than the design built and evaluated. In particular, a pair of designs incorporating anatomically aligned hinges were similar to the geometry of the BIME seats.

The first of these is similar to the seat designed and evaluated by Adlam et al[7]. It stabilises the femur and allows movement of the tibia and spine through extension of the knees and hips respectively. Patrangenaru criticises this design as it causes a substantial change in eye-gaze direction and head orientation when a spasm occurs; he also recognises that such as disruption to the occupant may reinforce spasm intensity.

The second seat concept proposed in Patrangenaru's work is a development of his first prototype that anteriorly tilts the seat base as hip and knee extension occurs, maintaining a vertical orientation of the trunk and placing the seat occupant in a near standing position at maximum extension (see Figure 2-2). It was specifically designed to reduce the rotation of the head, reducing vestibular and eye-gaze disruption.

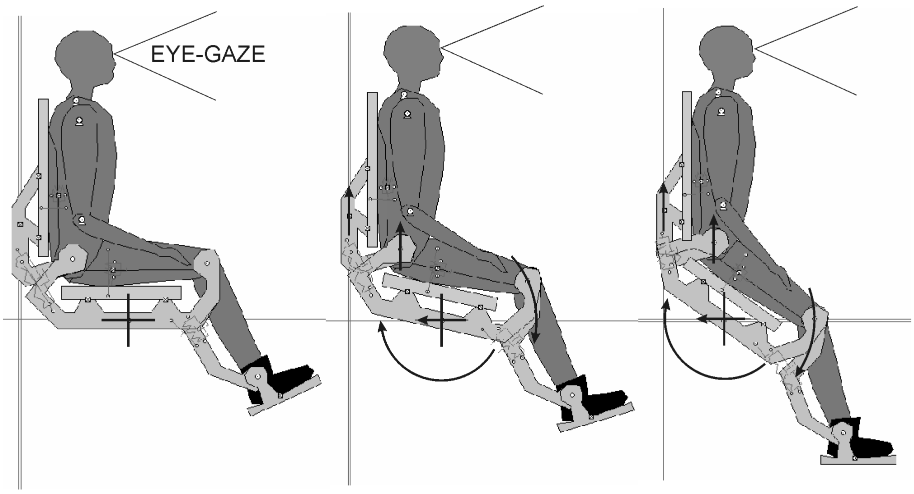

Figure 2-2: A redrawing of a sketch of an anatomically hinged seat from the 2006 thesis of V. Patrangenaru[6].

The conclusion of the thesis summarises the work completed, and identifies some trends:

1. Extensor thrust speed does not have a major impact on the occupant motion and forces during the thrust: the force and motion characteristic of the spasm is independent of its rate of development;

2. Extensor thrusts were shown to be largely independent of seat back friction.

The final conclusion of the thesis is that the alternative seat configurations proposed should be built and evaluated by patients, and that the pursuit of dynamic seating is worthy of further research effort.

This is a substantial body of work around the design of dynamic seating for children with extensor spasms. It builds an analytical model of extensor thrusting in a dynamic seat; presents a survey of professionals (and one wheelchair user) and their observations on extensor thrusting; and offers several possible design concepts, one of which was built and evaluated by healthy adults simulating extensor spasms. Sensor data collected from healthy volunteers was used to validate the model of the occupant and the seat and to guide the design. The work proposed several seat concepts that took account of the likely need of the seat users for head stability, anticipating the direction of the BIME research. The survey identified that children use spasm movement functionally, and speculated that they might learn to use dynamic seat movement functionally:

> "*Because the system accommodates different types of thrusts, the user will be encouraged to be more active and muscle use will be developed as the user learns to control and use thrust patterns necessary to accomplish self selected tasks.*"
>
> [6], Page 102

2.2.5 Patent Search

The work published by the research group at Georgia Institute of Technology[6] is the closest identified to the BIME research, thus a search for patents naming members of the Georgia team was made. Neither this search nor a further search for patents applied for by Georgia Tech combined with keywords [dynamic AND seat] yielded any results. Singhose and Sanborn both have patents granted, but not in this area of work.

74 patents related to compliant or dynamic seating were identified with a title keyword search on ESPACENET (an online patent search service run by the European Patent Office) for: `(dynamic OR compliant) AND (seat OR chair) NOT (valve OR vehicle OR tool OR automobile OR cutter OR stool)`

Most of these patents were for office or workstation seating, but there were notable and recent exceptions that incorporated dynamic seat backs for disabled people[23, 24, 10, 25].

JCM 'Triton Dynamix'

The abstract of the first of these patents is quoted below and the figure from the front page of the patent is reproduced in Figure 2-3.

> *"A seat back assembly (16) for a seat (10), comprising an upper seat back portion (24) for supporting an upper portion of a user's back and a lower seat back portion (22) for supporting a user's pelvis and pelvic region. The lower seat back portion (22) and the upper seat back portion (24) are independently adjustable. The upper seat back portion (24) can be reclined to one of a number of fixed angular positions and it is arranged and configured for dynamic angular movement under a load over a range of positions. The dynamic movement of the upper seat back portion (24) is controlled by a shock absorber (44) having adjustable damping means for providing a required level of tension and rebound in relation to the dynamic back action of the upper seat back portion (24)."*
>
> NOTE: Not all item numbers referred to in the patent abstract above appear in the figure given on the front page of the patent, which is reproduced in Figure 2-3.

FIG. 3

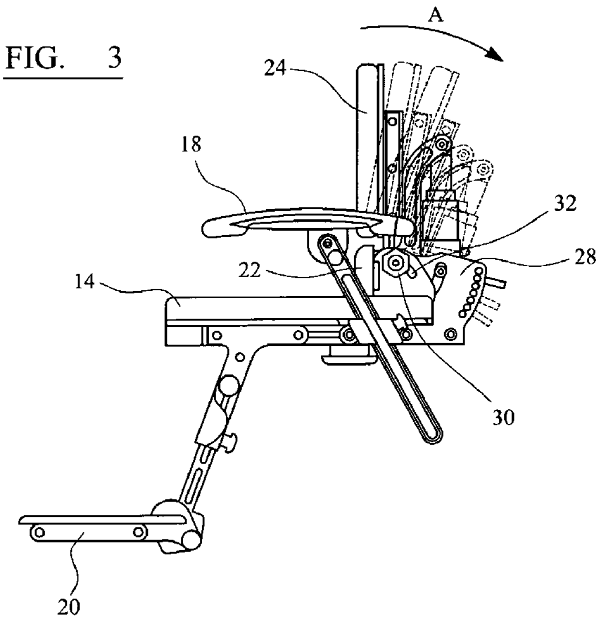

Figure 2-3: A reproduction of Figure 3 from JCM's world patent for a dynamic seat back mechanism. Patent Number: WO 2008 / 129231 A1

Interco 'AktivLine' Seat

A second patent on dynamic seating for disabled children (US Patent 6,488,332 [10]) was cited in Patrangenaru's work[6]. This patent is for a dynamic seat for children experiencing whole body spasms. It allows hip and knee extension, and maintains head orientation. It does not allow asymmetric movement of the legs. A drawing of the seat from the patent is shown in Figure 2-4.

Kids Up 'Rock Active' Seat

The 'Rock Active' seat is very similar to the Interco seat referred to above, and its US patent cited the Interco patent. The seat allows movement of the hips and knees. It was reviewed in a paper by Hahn et al[4]. A drawing of the seat taken from its US Patent[25] is shown in Figure 2-5.

2.2.6 Discussion

Research into the design and effectiveness dynamic seating is at an early stage. There are a few commercial products available at the time of writing, and similarly a few evaluations of some of those products. The most successful of those in the UK (the JCM Triton Dynamix and R82 X:Panda) were designed in response to the large forces and consequential metal fatigue caused by extensor spasms, and were not designed from clinical first principles. However, their increasingly widespread use and Patrangenaru's survey results[6] have confirmed that even simple dynamic seating is considered to be a viable option by professionals managing the posture and function of children experiencing extensor spasms.

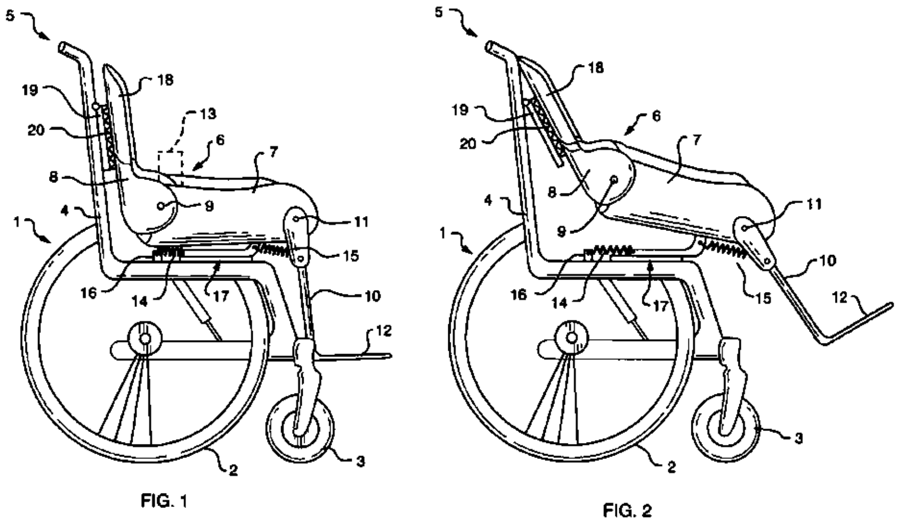

Figure 2-4: A drawing from the Interco US patent for the Aktivline seat. This seat is anatomically hinged at the hip and knee joints. It allows hip and knee extension and maintains head orientation, but does not allow independent movement of the legs.

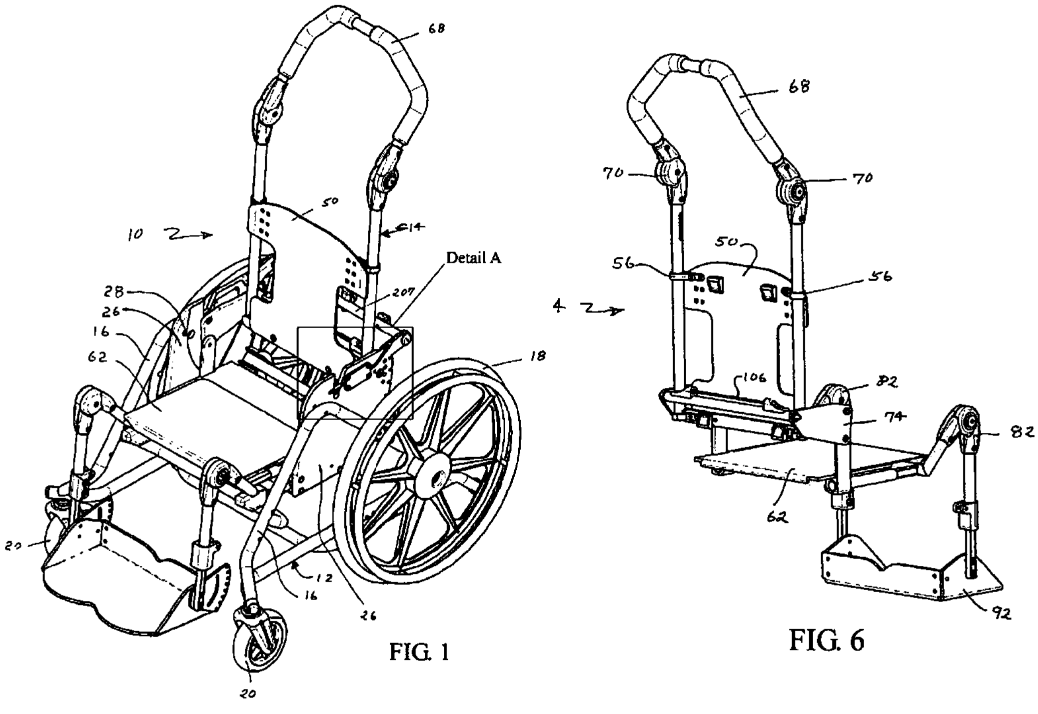

Figure 2-5: Two drawings of the Rock Active seat manufactured by Kids Up Inc in the United States. This seat is similar in concept to the Interco Aktivline seat[10], allowing extension of the hips and knees with anatomical hinges. Like the Interco seat, it does not allow independent movement of the hips.

Evaluation of these seats and others [2, 3, 4, 26] have shown that dynamic seating is likely to provide benefit to the child in posture, comfort (reduced skin contact pressure) and function. Evaluation methods have included clinical observation of children sitting in seats [4] and instrumented measurement of forces, pressures and movement[2]. The seats were designed with a variety of mechanisms, with some like the Interco and KidsUp seats having anatomic pivot points, and others, like the JCM and R82 seats having non-anatomic pivot points.

Research published thus far presents small studies of the effects of dynamic seating, and shows that it is likely to be beneficial for children with extensor spasms. However the neurological and postural mechanisms by which dynamic seating effects these improvements are not currently known. This is in part due to the lack of understanding of the causes of extensor spasms. Further research in this field is due and should focus on:

- The biomechanics of children seated in whole body and partial dynamic seating, including the measurement of forces, muscle activity and movement patterns. "How do children move, and what forces cause this movement?"
- The neurological mechanisms for the stimulation and suppression of extensor spams. "By what mechanisms do spasms initiate, sustain, and recede?"
- Strategies employed by children, parents and carers to accommodate, suppress and utilize extensor spasms. "What intuitive strategies do those experiencing spasms every day employ to mitigate their effects?"
- The design of dynamic supports, with reference to findings from the research areas described above. "How should dynamic supports (including seats) be designed to achieve maximum long term benefit for the child?"

2.3 Interventions for the support of the motor development of children with cerebral palsy: Providing a context for a child to learn postural control

Postural control of the body enables the person to position themselves for optimum functioning in any given context. Many factors contribute to the choice of posture, and given that desired functions and contexts are continually changing, posture also changes frequently. We know from our own experience that desired functions may be physical (raising a glass to the mouth), or psychological (concentrating the mind on solving a problem); and that we adjust posture to optimise our ability to carry out these functions within the environment in which we find ourselves. For example, a person drinking while sat on an outside seat on a warm summer day will adopt a more open posture than a person drinking at the same table on a cold windy winter day when heat conservation becomes an important function. Posture also changes with mood, temperature and the presence of others, as it is also used as communication. The posture adopted by a person at any one time is the result of a constant and mainly subconscious evaluation of many different factors. There is no such thing as an 'ideal posture' for a given task, yet many disabled children with cerebral palsy are fixed in static 'functional' positions for long periods of time[27] without the opportunity to adapt their posture.

This section of the literature review aims to demonstrate that children are able to adapt and modify their own posture from a very young age; that they progressively learn to control their posture; and that these abilities also apply to disabled children with cerebral palsy; thus laying the foundation for possible gains in function from the use of dynamic seating.

As well as providing comfortable seating for children with whole body extensor spasms, this work also aims to design seating that provides children with poor postural control with a context in which they can learn to adapt their posture to support their functioning.

The first subsection (2.3.1) identifies studies where postural control has been shown to contribute to meaningful function. The second subsection (2.3.2) briefly describes the process by which a child learns postural control, and comments upon the ability of children with cerebral palsy to do so.

2.3.1 Postural control and adaptation makes a significant contribution to meaningful functioning.

This subsection aims to demonstrate from the literature that children use the adaptation of posture to support functioning from an early age, and continue to so as they develop. For example, when considering the environment and positioning of neonates in the neonatal intensive care unit (NICU), Inga Warren writes:

> *Positioning is about comfort and functional posture."*[28], p463.

She asserts that static posture is not conducive to developmental progress or to self-regulation. Positioning that suits a baby is that which allows him to function as normally as possible; that is:

"[positioning] which allows him to sleep best when he wants to sleep, to communicate his needs, to interact with his carers when he is ready, and to be most competent at regulating his own physiological functions to achieve stability and energy conservation."[28].

In this paragraph Warren has identified four key areas where posture has an impact on the ability of the infant to function:

1. Sleep / rest;
2. Communication;
3. Social interaction;
4. Self-regulation (homeostasis).

These areas of functioning remain key to overall well-being throughout childhood. As children grow up from infanthood through adolescence into adulthood, positioning and the ability to control posture continue to enable or disable children from functioning in these areas.

As a child develops, additional areas of functioning emerge such as mobility, play and education. Postural adaptation is also employed in these contexts. Examples of the links between positioning and functioning[12, 13, 29, 30] are given below:

An example of where postural adaptation impact the ability of a child to function is described by McEwen and Karlan[12]. They assess the impact of posture on the ability of two children aged 35 and 39 months to use a communication board. Both children were diagnosed with spastic quadriplegic cerebral palsy. Both children were assessed with a battery of physical and psychological tests. Their scores on these assessments are shown in Table 2.1.

Domain	**David**	**Chris**
Brigance Diagnostic Inventory of Early Development[31]		
Gross Motor	4 months	5 months
Learning Accomplishment Profile (LAP)[32]		
age at measurement	*32 months*	*29 months*
Fine Motor	2-3 months	5-6 months
Self-help	5-9 months	12 months
Socialization	21-24 months	Not Assessed
Cognition	18 months	8-9 months
Sequenced Inventory of Communicative Development - Revised (SCID)[33]		
age at measurement	*35 months*	*36 months*
Receptive Language	24-28 months	24 months
Expressive Language	16-24 months	10-12 months

Table 2.1: A table of the assessment results from McEwen's 1989 paper[12] describing the initial assessment results of the two participants in research measuring the effect of positioning on the ability of a child to communicate using a communication board.

McEwen measured the ability of the two boys (Chris and David) to communicate with staff while positioned in four different pieces of positioning equipment: a chair, a stander, a prone wedge and a sidelyer. Their functional outcomes when positioned using these pieces of equipment were significantly different according to how they were positioned.

The task used to assess function was pressing a switch on a communication board. If the switch was operated, it activated an electrically powered toy. The experiment measured the ability of the boys to operate a switch in each of six positions distributed across a board marked out in 2.5 inch squares. Response latency was chosen as a physical factor to measure because the ability to make rapid selections is important in the use of Augmented and Assisted Communication (AAC) systems.

After being placed in one of the four postures referred to above, the children were asked to activate the pressure switch which was randomly placed on the board in one of six possible locations. Latency was measured using a stopwatch.

The study, which compared latency times in four different postures and six switch positions concluded that sidelying reduced the ability of children to function in switch pressing. This was thought to be so for two reasons:

1. The children had greater difficulty extending their arms and flexing their shoulders to the reach the switch when in the sidelying position. This resulted in longer activation latencies.
2. The modified visual orientation of the task when the child was in a side lying position was also considered to have contributed to the reduced functioning.

Lesser differences in response latency were observed when the children were positioned in the seat, prone wedge and stander. It was observed that the latency times for David were lower when he was in the stander. He was thought to be able to use his hands more effectively in this position, though reasons for this were not postulated. Chris was observed to tire more quickly on the prone wedge, which increased his latency times.

McEwen concludes that:

> *"the results suggest that thorough assessment of the influence of position on the functioning of other individuals with cerebral palsy, and the effects of positioning devices on other activities of David and Chris could be of value"*
>
> [12] p241

In her 1992 paper[13] McEwen writes about about another experiment to measure the effects of positioning on communicative interactions between school students (aged between six and twelve years) and classroom staff. The study observed students and staff interacting in the classroom with the students positioned in either a wheelchair, a sidelyer or "freestyle" and relatively unconstrained on a floor mat with some support from cushions or pillows.

The measured variables were socio-communicative behaviours classified as either *initiation of communication* or *maintenance of communication*. Adult communicative behaviours were mostly spoken, whereas the children communicated by a variety of means including facial expressions, eye gaze and non-verbal vocalizations.

Experimental sessions in the students' classroom were recorded using a video camera. Each session consisted of a five minute unstructured period where the staff were asked to go about their normal activities, followed by a structured communication routine. The sessions were structured as shown in Table 2.2:

Minute	Activity
0	*Unstructured interaction*
5	*Establish proximity* - The adult approached the child but did not communicate with the child unless the child initiated communication.
6	*Look attentively* - The adult looked at the child and responded to any student initiations.
7	*Talk for 20s* - The adults prompted and attempted to engage the student by talking for 20s.
9	*"Do you need help?" questions* - The adults again prompted the child and attempted to engage the child by asking if he needed help. If no response was received within 10s, the question was repeated.
11	*Parting comment and leaving* - The adult gave a parting comment, paused for 10s and then walked away.

Table 2.2: A table showing the sequence of events in sessions described in McEwen's 1992 paper[13] about the effect of positioning on the ability of two children to use communication boards.

Initial observations showed that five of the students communicated considerably more than the others. and consequentially received more interaction from the adults. This group was functioning in communication at a higher level than the remaining students.

The results of the study were presented in categories: adult initiations, student initiations, maintenance of communication, and observations during the structured routine:

Adult initiations during the unstructured period at the beginning of the session were few in number – 0.12 times/minute - fewer than one per session. Adults initiated substantially more interactions with the more able group, and with students who were sitting in a wheelchair rather than using the sidelyer or floor mat.

Student initiations were more frequent, averaging 0.4 per minute. There was no significant difference in the frequency of student initiations when analysed by group or position.

Communication maintaining behaviours (responses to communication within 30s) were infrequent because of the low frequency of communication initiations – the adult communication maintaining behaviour scores were *"too low to include in the statistical analysis"*.

Student communication maintaining behaviour frequencies were independent of position. However only one student from the less able group scored an instance of a communication maintaining behaviour.

Students from the less able group communicated for a higher proportion of the structured session when lying 'freestyle' on a floor mat (0.32) compared with sidelying (0.12) or sitting (0.21). The higher functioning group showed less variation by position. This effect was more pronounced when measured by absolute communication duration rather than proportionally with the freestyle, sidelying and sitting durations being 200s, 50s and 60s respectively.

In her discussion, McEwen concludes that the effects of positioning on communication by children with profound multiple disabilities are complex, but also notes that position is a significant control parameter in the initiation of communication by adults, and in interactions by lower functioning students with an engaged communication partner.

Adults tended to initiate communication with students who were sitting, and who were recognised as being in the higher functioning group. Comments such as “Uh oh, she’s lying down, she’ll go to sleep.” suggested that adults expected children who were not sitting to not communicate. The results suggest that their own efforts at communication reflect this belief, whereas the students made a greater effort than the adults to communicate whatever position they were placed in.

McEwen did not expect to find that students of lower ability positioned ‘freestyle’ on a floor mat would communicate more than those positioned more rigidly in specialist seating, however this was the case. This suggests that the ability to move granted by the freestyle positioning is taken advantage of by the children.

Discussion

McEwen and Warren’s research indicates that children will make use of opportunities for movement afforded to them by dynamic seating, even if they have severe disability. All children want to communicate, and are ingenious in finding ways to do so, using posture, vocalisation and technology. The need for communication is driven by the fundamental needs for relationship and the expression of personhood. Static seating not only changes the child’s ability to communicate, but also changes adult’s expectations of communication. Children’s opportunities to form and maintain relationships are damaged by immobilisation that prevents them from gaining attention and expressing themselves as they would if they were able to move. Dynamic seating may change not only the child’s relationship with the carer, but also the carer’s relationship with the child. It would be interesting to develop research into the relative priorities that children with severe disability place upon communication and fine and gross motor function.

2.3.2 Child development and postural control

At twelve weeks gestation, a fœtus in the uterus of a woman is an active organism, demonstrating a rich repertoire of coordinated movement of its limbs, head and torso[34, 35]. The neuromotor development of the child towards mature motor control has begun, and continues without interruption until maturity after adolescence[36].

The repertoire of spontaneous unstimulated endogenously generated movements of the fœtus have been observed and classified by Prechtl[35]. At first sight these movements appear to be random and uncoordinated, however they follow coordinated patterns, remaining substantially unchanged until two to three months after birth.

At about three months an important transition occurs in the child’s motor development. The neuromotor system adapts to life outside the uterus and the child starts to make directed movements to support simple functions such as head control, balance and reaching[36]. As the child develops, he gains the finer and more coordinated control needed for more complex functioning such as sitting or standing. Children aged 3-4 months start to employ direction specific postural control strategies to enable reaching and grasping. In an observational and EMG study of how children effect reaching [37], De Graaf-Peters states that:

> "...within the age period of 46 months infants develop the capacity to select better postural patterns, i.e. postural activity which was associated with reaching movements with a better kinematic quality."
>
> [37], page 654

By eight months, most children can sit without assistance or support and by one year many can stand unassisted, some may even be walking[38]. These skills are developed through a process of experimentation: trial and error. Children *learn* to reach, sit, stand and walk through a process of progressive experimentation and learning, gaining skills and control which build upon one another even as the brain is developing and providing the means for this control to occur. The ability to walk is not innate - it is learned. Children who are deprived of the opportunity to learn to walk cannot walk, however they can subsequently learn to walk; as cases where children have been rescued from severe deprivation have demonstrated[38].

Reaching and grasping follow a similar pattern of development. Infant grasping reflexes disappear and are replaced by initially simple, but then progressively more complex control of the hands, arms and trunk. Control of the head, which develops first, is important for gaining control of the hands, as the child's sight of his hands helps with learning how to control them.

By the end of the typically developing child's first year, most, if not all of the most significant motor control objectives are already in place. The child, without being 'taught', has gained control of a highly complex multi-degree of freedom, kinematically redundant system, and is able to control it dynamically to effect its own objectives.

Returning to [36], De Graaf-Peters studied the sitting and reaching strategies of typically developing children and children with cerebral palsy and made the following key findings (in italics) which have been commented upon:

1. *Little is known about the development of postural problems in children with cerebral palsy; and this knowledge is needed for the development and evaluation of therapeutic interventions.*

   This is very true for the development of dynamic seating. Present design efforts are not based upon a theory of the development of postural control.

2. *Children with CP showed direction specific activation from 15 months onwards.*

   In typically developing children this occurs at one month. The children with CP are possibly developing on the same trajectory, but are substantially delayed.

3. *Top down recruitment strategy might indicate that stabilising the head is a major goal of postural control.*

Seating should permit and assist children in their aim of controlling head position.

"The major postural dysfunction of children with CP is the substantially reduced capacity to modulate the degree of postural muscle contraction to the specifics of the situation".

Children with cerebral palsy find modulated control of posture difficult. Dynamic seating may provide a context in they can learn modulated control.

Towards the end of the paper, De Graaf-Peters reports on an evaluation comparing two training interventions (traditional physiotherapy and COPCA training) with typically developing children by measuring their degree of postural control using the EMG analysis and observation from the earlier research reported in this paper. On the final page (p1198), she writes that:

> *"The two studies on the effect of intervention on postural development in children with or at risk for a developmental motor disorder indicate that* ***intervention which requires active trial and self-produced variation and error experience is able to improve postural control.*** *The data also suggest that the more traditional approach of intervention such as NDT, which involves a substantial amount of handling and provision of postural support, is not effective in improving postural development."*

Dynamic seating offers an opportunity for free experimentation with movement and postural control to severely disabled children with cerebral palsy. The work of De Graaf-Peters, Warren and McEwen suggests that such an intervention would be actively exploited by children striving to learn to control their bodies and especially their heads. This final evaluation and outcomes from this work (Chapters 15 and 17) have supported this hypothesis with the observation of learned postural control by a child with severe cerebral palsy sitting in a BIME dynamic seat.

Chapter 3

Children with Extensor Spasms

The seating that is the subject of this work has been designed for children with severe movement disorders and whole body extensor spasms. Examples of conditions that result in movement disorders in children include:

Cerebral Palsy (CP): Problems with the control of movement caused by damage to the brain before, during or after birth. The nature of the disorder depends upon which regions of the brain are affected. The brain damage is not progressive, though some sequelae may worsen in time. CP is the main cause of extensor spasms in children.

Other neurological diseases: Other rare conditions such as Rett Syndrome may cause neuromotor disability, including extensor spasms in children.

Muscular Dystrophy (MD) / Spinal Muscular Atrophy (SMA): Progressive muscle wasting diseases that cause weakness as muscle is lost. MD and SMA are both terminal. Children with MD and SMA do not experience whole body spasms.

Most, though not all, of the children that are likely to benefit from the seating designed in the course of this research are likely to have Cerebral Palsy, so a more detailed description of this condition is given below.

Cerebral Palsy is defined as being an impairment of movement caused by damage to or an abnormality of the brain: Cerebral - of the brain; Palsy - Impairment of movement. It is usually the result of complications at birth or of complications occurring after premature delivery, such as deprivation of oxygen to the brain (ischaemia or anoxia), infection or hemorrhage. A short definition of cerebral palsy is given by Bax[14] as:

> *"Cerebral palsy (CP) describes a group of disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, cognition, communication, perception, and/or behaviour, and/or by a seizure disorder."*

Cerebral palsy is a complex and multi-faceted syndrome that is the result of an injury to the developing brain. The brain is vulnerable during its early development, and especially so from before birth until a baby is about six months old. A good introduction to the causes and symptoms of cerebral palsy is given on the NHS website[39] [1], and is summarised here:

Causes of Cerebral Palsy

Periventricular Leukomalacia (PVL): This is damage to the white matter of the brain. It is thought to be caused by a reduction in blood supply to regions of the brain. PVL can be caused by a maternal infection such as Rubella; maternal hypotension; premature birth, especially at 24 weeks or earlier; maternal cocaine use during pregnancy.

Abnormal development of the brain: There are many causes of abnormal brain development, including genetic mutations; infection such as herpes, toxoplasmosis or physical trauma to the head.

Intracranial hemorrhage: Bleeding can cause damage damage to the brain through loss of blood supply or through the action of the blood on the brain itself. Intracranial hemorrhage normally occurs in unborn children as a result of a stroke. A stroke may be caused by pre-existing weakness in the child's blood vessels, maternal hypertension, or infection in pregnancy. Hemorrhage can also occur after birth. Intraventricular hemorrhage (IVH): a hemorrhage within the ventricles inside the brain is common in extremely premature babies and can also cause PVL.

Trauma: Cerebral palsy can also be caused by trauma to the brain which may be caused by physical or biological action. Examples include severe impact to the head and bacterial meningitis.

Cerebral palsy may present in several different ways, each of which may or may not be present in a child with a diagnosis:

Spasticity This is abnormal muscle tone that occurs during voluntary or passive movement. It results in difficulty with control due to muscle stiffness. Spasticity can cause serious problems with joints and the skeleton if the posture of the child is not managed correctly. Even with good postural management, it can be difficult to avoid some deformity in the longer term. Spastic CP occurs in both legs (diplegia), the arm and leg on one side (hemiplegia) or all four limbs (tetraplegia).

Dyskinesia (Athetosis) Cerebral palsy can also manifest as problems of control. Athetosis is continuous involuntary movement of limbs and body, but particularly the limbs. The movements of the limbs are not controlled, and are slow and writhing, being caused by alternate contractions and relaxations of agonist/ antagonist muscle pairs. Athetosis can become more pronounced when a child is attempting a controlled movement.

Ataxia This is a rarer form of cerebral palsy that results in problems with precision of control, coordination and balance. It impairs fine control of position and velocity. Ataxia is also associated with

[1] Excellent information on the characteristics, causes and treatment of cerebral palsy is available on the NHS website: `http://www.nhs.uk/conditions/cerebral-palsy`

problems with spatial awareness. It is not associated with the increased muscle tone that occurs in spastic and athetoid CP, and affects the whole body. It can cause some reduced muscle tone (hypotonia).

Dystonia This is a form of CP that is more complex and can present as a complex disorder of muscle tone, hypotonia, hypertonia and intermittent spasms [such as those that are the subject of this seat design]. Supporting children with dystonic CP presents a great challenge to the therapy team formed around the child.

The population being studied in this work is children with dystonic CP who are unable to be seated successfully in conventional rigid seating system (see Figure 3-1). They may also have other CP sequelae such as dyskinesia and spasticity. Presentation of dystonia in the included population includes whole body spasms of the extensor muscles i.e those muscles that cause the limbs to straighten and the spine and neck to arch backwards. Some children also exhibit flexor spasms which cause the limbs to retract and the spine and neck to arch forwards. Spasm frequency varies significantly between children, but can be as frequent as thirty episodes every minute if the child is stressed or inappropriately supported.

3.1 Population size

The population of children for whom the new whole body dynamic seat is intended is thought to comprise about fifty individuals in the UK. This number is an estimate by the head of therapy at Great Ormond Street Hospital[40], based upon the number of referrals they receive. The exact number is not measured by the NHS and is unknown. This would scale to 378 children in Europe.

Himmelmann[41] measured the birth rate in Sweden for children with dystonic cerebral palsy to be 0.27/1000 births. This suggests there are 1400 children born every year in Europe and in the UK with dystonic cerebral palsy, assuming birth rates are the same.

The EPICure study group[42] identified that 10% of live births between gestations of 22 - 25 weeks result in severe neuromotor disability (103 children/year). This figure scales to 6800 children born in Europe each year, assuming birth and survival rates are the same.

3.2 Living with Whole Body Extensor Spasms

The intensity, frequency and duration of spasms are highly variable and are affected by many factors, including fatigue, the child's emotional state and the child's ability to exercise a limited degree of voluntary spasm suppression.

3.3 Recruitment

Recruiting children to the project was difficult as the inclusion criteria for the research defined a subset of the total population for whom the generalised chair might be suitable. A large number of schools and therapy services were contacted by the occupational therapy team.

Figure 3-1: A photograph of a commercial rigid seat for disabled children. The photograph shows the usual features on a seat such as this including: Adjustability for size and position, a head support, lateral thoracic supports, a mobile base, adjustable footrest, and lateral hip supports. This seat was used regularly by one of the research participants until it fractured as a result of metal fatigue caused by his powerful extensor spasms.

Recruitment was by written contact with schools, Child Development Centres and Occupational Therapy and Physiotherapy departments based in hospitals and community settings. An information sheet describing the project and the child and families expected involvement was sent to the centres, along with a covering letter and a screening form. Initially centres were chosen for geographical proximity to Great Ormond Street Hospital or Bath Institute of Medical Engineering. However due to the small population of children meeting the inclusion criteria, the recruitment area was expanded nationwide.

The screening form was devised to collect data to demonstrate whether the child met the inclusion criteria, along with some background information on their difficulties using currently available seats. The screening form was completed and returned by local services for children they felt may be suitable for the project. Children who were potentially suitable for recruitment were visited by the project team where an assessment was carried out.

Of the screening forms returned, most were rejected. The commonest reason for rejection was that the child was at Chailey Sitting Ability Level 2, not Level 1.

Once identified as suitable participants, informed consent was gained from the childs parent, and a second set of forms was completed for collection:

- Demographic data and background information;
- Current seating and seating history including subjective views from the childs carers;
- Physical assessment;
- Childs measurements.

The child and its parents were invited to Great Ormond Street Hospital for a project admission assessment, as it was a requirement of the research that the children participating should be registered as patients at Great Ormond Street Hospital. At the hospital, they were assessed in a spinal clinic, a spinal x-ray was taken, and the child's movements were video recorded for future reference. A letter was sent to the childs General Practitioner informing them of the childs involvement with the project.

3.4 Inclusion and Exclusion Criteria

The inclusion criteria for the project were defined in terms of a child's ability to sit and the presence of whole body extensor spasms. Some children also exhibited flexor spasms immediately after extensor spasms, but this did not exclude them.

The inclusion criteria were:

1. That a child should have a Chailey Sitting Ability[43, 44] level no greater than one. This implies that the child cannot be placed in a sitting position without external support. Green and Nelham[43] describe a child at Level 1:

   > *"At this ability level a child cannot achieve or maintain a sitting posture, that is he cannot anchor his pelvis or dissociate the movement of his trunk from his lower body.*

Prescriptive seating is required to provide postural fixation, especially stabilisation of the pelvis."

Children at Chailey Sitting Ability Level 1 could also be assessed at the more severe end of the Gross Motor Function Classification Scale Level Five (GMFCS V). A child at GMFCS V is described in [22] as follows:

> *"Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for through the use of adaptive equipment and assistive technology. At level V, children have no means of independent mobility and are transported. Some children achieve self-mobility using a power wheelchair with extensive adaptations."*;

2. That a child is unable to be successfully seated in conventional seating;

3. The child should be age 3-7 years;

4. Diagnosis of a neurological disorder, such as cerebral palsy;

Inclusion also requires the cooperation and consent of a parent or primary carer and the child's occupational or physiotherapist.

The exclusion criteria were:

1. A diagnosis of epilepsy, especially if the epilepsy causes spasms. This is because it was important to be able to distinguish between extensor spasms that are a result of the neurological movement disorder, and those that are the result of epilepsy;

2. Concerns regarding the development of the spine or pelvis, such as a developing scoliosis.

3.5 Recruited Children

This section describes the results of the medical assessment of the children recruited to the project. Each child was assessed at a spinal clinic at the Great Ormond Street Hospital in London. This is a tertiary hospital specialising in child health and is a national centre of excellence for the assessment of and interventions for neurological disability.

Two boys were recruited to the project although it was intended that three should be recruited. They both had cerebral palsy resulting from brain damage received during a traumatic birth and subsequent medical complications. The two boys are coded as R1 and A1 for this work, to protect their anonymity.

3.5.1 Child R1

At the time of assessment, Child R1 had spastic / dystonic fourlimb cerebral palsy secondary to premature delivery at thirty four weeks due to placental abruption (rupture and haemorrhage); a Gross Motor Function Classification Score of five (GMFCS V); and cortical visual impairment.

Problems: Gastrostomy fed with a Nissen's Fundoplication (restriction of the lower oesophagus to prevent acid reflux).

Observations: Spinal kyphosis (forward spinal curve) but no scoliosis (lateral spinal curve) due to truncal hypotonia (reduced muscle tone). He flexed to his right hand side.

O/E: R1 had mixed spastic / dystonic presentation with asymmetric range of motion at the hips.

- 45° abduction with hip flexion to the right;
- 30° abduction with hip flexion to the left;
- A bilateral catch at 20° abduction and bilateral popliteal angles of 50° with a dynamic catch at 90°.
- His knees were difficult to flex due to dystonia in his quadriceps, though it was possible to move his ankles to 10° dorsiflexion if the knees were extended. His dynamic range was contributing to his inability to sit.
- In July 2010, attempts to continue overnight feeds were unsuccessful due to his frequent spasms.
- He had extensor spasms in his trunk, hips, knees and left upper limb; and occasionally a flexor spasm of the hips that was not painful.
- He had extreme scissoring of the leg with marked asymmetry due to more involvement of the right side since a prolonged seizure in 2010.
- He had no fixed contractures, and no cardiac or renal problems.
- R1 had asthma.
- R1 was aged 5y at the time of recruitment.

3.5.2 Child A1

Child A1 was recruited from a school in London. He has spastic / dystonic cerebral palsy due to medical complications following his preterm delivery.

Background: At the time of recruitment, A1 was a 5 year old boy with a diagnosis of 4-limb dystonic cerebral palsy with poor vision. He attended a Special School where he received specialist support from Occupational Therapy, Physiotherapy and Speech and Language Therapy. A1 was one of triplets (all male).

When initially assessed for the project A1 was sitting in a Leckey Squiggles chair at school and using a Chicco buggy for transport at home. In the home he was using a Jenx Whale chair and a Rifton corner seat.

Motor pattern: A1 presents with fluctuating muscles tone, generally increased, although this reduces with flexion. He has some asymmetry, being tighter on the right than the left side. His total body extension pattern is symmetrical with significant hip adduction. He also has some flexion spasms. Both asymmetric tonic neck reflex and symmetric tonic neck reflex remain present. Currently A1 has no orthopaedic monitoring and his spine remains flexible. Examination of the range of movement in his lower limbs (significant for a seated position), were all within the normal limits with the exception of hip extension which was 5° from full on the left and on the right both knee (-10°) and hip (-15°) were restricted.

Difficulties with sitting: A1 required full support in sitting, with a Chailey Sitting Level of 1 (unplaceable). When provided with supportive seating there was a reported history of difficulties, mainly relating to his strong extensor thrust. At the start of the project his main problems were identified as:

- Resistance to going into current chair, extending immediately, resulting in it being difficult to place A1 in the chair;
- Getting "stuck" in an extension pattern;
- Bottom sliding forward against or under the pelvic strap;
- Adduction causing discomfort;
- Requiring frequent repositioning during the day.

The main barrier to A1 being able to sit comfortably in supportive seating was identified as his extensor pattern.

A1 attended the Neurospinal Clinic at Great Ormond Street Hospital. Baseline x-rays were taken and A1 was reviewed by an Orthopaedic Surgeon, Neurologist and Specialist Occupational Therapist. At the time of appointment A1 was noted to have a flexible spine with no significant concerns. A future concern raised was the potential development of a kyphosis (forward curve of the thoracic spine) due to low truncal tone and an inability to maintain an upright seated posture.

3.5.3 Child J1

Child J1 was recruited specifically for a single short evaluation. He did not meet the project inclusion criteria, but evaluated the first independent seat because he was the same size and a similar build to Child R1. He was able to speak and describe whether the seat was comfortable. He was seen by a paediatrician from Bath and North East Somerset Community Primary Care Trust Community Child Health Team, and was very well known to the project team prior to the research programme.

Due to extremely premature birth, Child J1 presented with the following status:

- Ataxic cerebral palsy due to cerebellar damage;
- No spasticity;
- No spasms;
- No spinal or other musculoskeletal concerns;
- Full range of motion;
- No medical concerns.

Part II

Methods

Chapter 4

Soft and Semisoft Prototyping: Evaluation Methods for Dynamic Support Concepts

This chapter describes a novel response to the challenges of iteratively designing complex dynamic seating systems. The approach is user centred, valuing the child and those who care for and about him. Soft prototyping enables early engagement with a severely disabled user at the concept design stage before any commitment to hardware is made. Semi-soft prototyping enables a smooth transition to be made from user evaluation of a concept to user evaluation of a complete physical embodiment. This method has been essential to the success of this work, reducing the human unknowns and accelerating the design process. It enabled a new support design to be evaluated such that the risk of adopting it was reduced to a level acceptable within a time and resource constrained project.

4.1 Iterative Design

The design of assistive technology for disabled people cannot be effectively achieved using conventional engineering design methods such as might be applied to the design of a gearbox or a girder bridge[45, 46, 47]. In the latter contexts, the problem to be solved can be clearly identified and described. A detailed specification can be developed before design begins, because the problem can be almost fully understood from predetermined, observed and measured knowledge of the context in which the proposed solution must work.

Where a designer is solving a problem related to a disability, the problem cannot be fully understood or described prior to beginning design. It is not possible to anticipate every aspect of complex human interactions with a device, or predict how a person will respond to certain aspects of a human interface without building that interface. Indeed, a disabled person may not fully understand a problem he is asking an engineer to solve, as he may not have experienced the impact of a device on his perceived problem. The evaluation of a device designed to solve a problem, can, even if it is imperfect, yield insight into the problem itself. Thus it is necessary to work using an iterative method that facilitates progressively building understanding of the problem being addressed through exploration of the problem by user evaluation of a series of prototypes using measurement and detailed observation to guide the next design next stage.

It is this process of problem exploration and cyclic design, user evaluation and redesign that is known as *iterative design*, and it is key to working successfully in the field of assistive technology and with disabled people.

4.2 Introduction

It is important to involve potential users of new assistive technology in the process of its design, to ensure that the resulting devices meet the actual needs of the user rather than the user's needs as perceived by the designer. Careful user evaluation of early prototypes is one means by which user input into the design process may be achieved.

Evaluating assistive technology for children with complex disabilities as part of an iterative design process[45, 47] requires a substantial investment in time. Each design-build-evaluate iteration requires a prototype to be designed in detail, built, and then tested by disabled users; before its effectiveness can be known. In the early stages of the development of a novel device, there is a high risk that the whole concept adopted by the designer will be unsuccessful. It is possible that the early stage prototype will be found to be unsuitable by the team after a short evaluation period with very little useful data or observation of a child's response to the prototype being gained. It would be helpful if this risk could be reduced prior to committing to detailed design, by enabling some data to be gathered about the likely outcome of the evaluation and the child's physical response to the concept.

It would be beneficial, at the earliest stages of design, to enable the user to experience a realistically simulated user interface whilst being observed. These observations provide information that may suggest which concept should be pursued. After a potential solution has been identified, evaluation of higher fidelity prototypes is required. These prototypes should more closely resemble the selected solution than previous prototypes, so that their user interface can be checked prior to committing to substantial detailed design and manufacture.

This chapter describes two techniques used for the evaluation of prototypical dynamic devices for the support of children with complex movement disorders resulting from cerebral palsy. The methods were applied early in the design of a dynamic seating concept for children with whole body extensor spasms who had not previously been successfully seated in conventional rigid paediatric postural support systems.

Soft and semi-soft prototypes can fully or partially substitute a mechanical prototype for *early stage* user-evaluations. Soft prototypes employ a coordinated team to directly support the evaluator in the same way as the concept being tested. Semi-soft prototypes are non-rigid partial implementations of mechanical systems that are operated by a coordinated team.

These methods are similar to and were inspired by the 'Wizard-of-Oz'[48, 49] process widely used in the evaluation of intelligent human computer interfaces. However in this case, rather than a person enabling a simple digital system to simulate artificial intelligence, human support is used to endow a

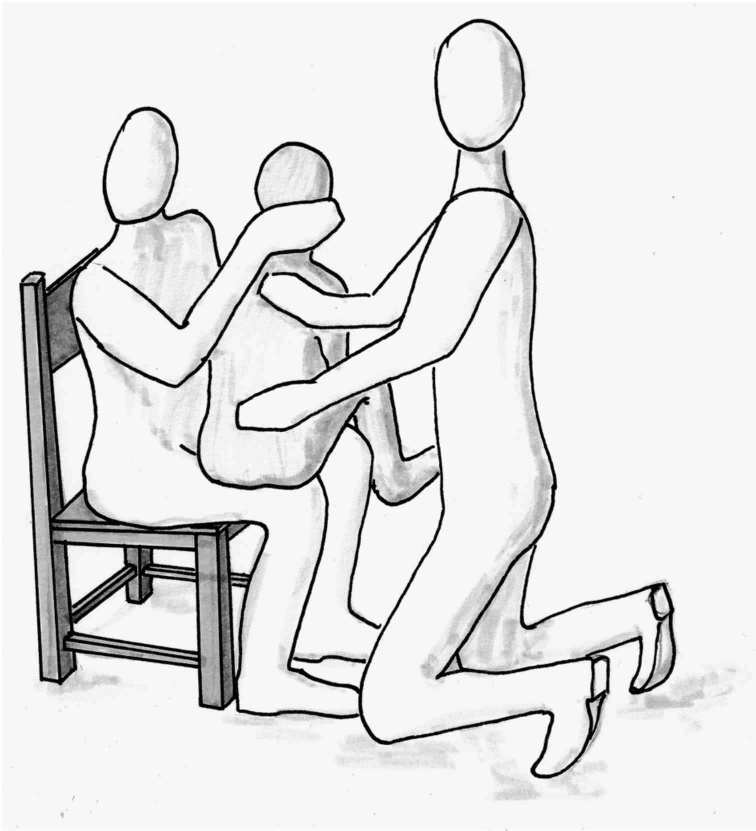

Figure 4-1: A sketch showing some members of the team for a soft prototype evaluation of a dynamic backrest in progress. The participants shown are LEFT: parent (supporter / advocate) CENTRE: child (evaluator) RIGHT: therapist (supporter / leader).

simple mechanical system with additional dynamic properties that it would not otherwise possess. Thus evaluation of the user interface of such a system can be achieved without the need to design and build the mechanism that provides those properties; and the dynamic properties of the mechanism can varied at will.

4.3 Tools to Support a User Centred Design Methodology

The old arrogance of some lone designers who are convinced that 'they know best' is being replaced by a new and welcome humility. Designers and engineers recognise that they do not have universal experience, and that the contributions to design of potential and actual users of their products are key to the success of their designs. The point at which user engagement is introduced into the design process is progressively moving from a brief post design evaluation 'to check that we got it right' towards direct and fundamental influence over product definition and initial concept generation. However, effectively engaging highly disabled users in this process presents a challenge. It is difficult to engage with a child who cannot speak, who cannot describe his experience of his seating, and who cannot communicate speculation on improvements that might be made. Allsop et al recognised that:

> *"There is a need to develop an understanding of participation from children with disabilities in daily life activities, and to consider research designs that can accommodate these children."*
>
> [47], p3

Allsop[47] discusses the use of participatory design methods originating from Human Computer Interface (HCI) research and recommends that such methods are translated into assistive technology research with care, ensuring that the impact of the child's disability on her ability to communicate is taken into account. The soft and semi-soft prototyping methods described in this chapter provide a means for a severely disabled non-verbal child to meaningfully contribute to the early concept design phase of a product design project.

This chapter describes methods of concept evaluation that enables the most severely disabled child to meaningfully contribute to the early concept evaluation phase of a project, and to continue to provide useful guidance to the design team as the project progresses through prototype evaluation towards the completion of design. These methods are particularly relevant to the design of dynamic systems, where the complexity, duration and cost of prototyping are greater than with static systems.

4.4 Soft Prototyping

The therapy and engineering team took the concept of 'Wizard of Oz'[48, 49] interface evaluation used by the author in previous work in smart systems for people with dementia, and applied it to the design of seating for disabled children, employing its principle of simulating the function of a complex user interface using direct human control or communication.

Figure 4-2: A soft evaluation of a saddle seat concept by two therapists using a positioning roll as a simple prop.

4.4.1 The Soft Prototyping Method

Soft prototyping is a tool for quickly exploring multiple support concepts for the purpose of identifying which are most likely to be suitable to meet the needs of a person with a complex disability, without building physical prototypes for evaluation. A physical prototype is substituted by the coordinated actions and direct support of trained people, with perhaps a little simple equipment such as a positioning roll or a block for sitting. The soft prototype can be quickly adapted as its effects and utility are evaluated, and a series of alternative concepts explored with no engineering design and manufacture required. See Figure 4-3 for a flowchart of this process.

The effectiveness of the team that carries out a soft prototype evaluation can be made or broken by its integration and coordination. It is important that the team is carefully chosen to reflect a range of skills, as well as the ability to work together and communicate effectively. Several different roles have been found to be useful by the author in the course of his work:

1. *Evaluator.* The evaluator is the focus of the evaluation. This person, who may be a child or an adult, faces an intense experience during an evaluation. He or she is the focus of attention for a team working to achieve a more precise understanding of the evaluator's clinical need, and then developing a solution concept that is likely to meet that need. Close attention should be paid by the team to the evaluator's verbal and non-verbal communications.

2. *Team leader.* The evaluation leader may not necessarily be the manager of the members of the team. The leader should be a person who can consider the broad objectives of the evaluation task, including aspects of concept design, physical support strategies, biomechanics, movement disorders and the management of the evaluator's emotional state. The leader may not necessarily

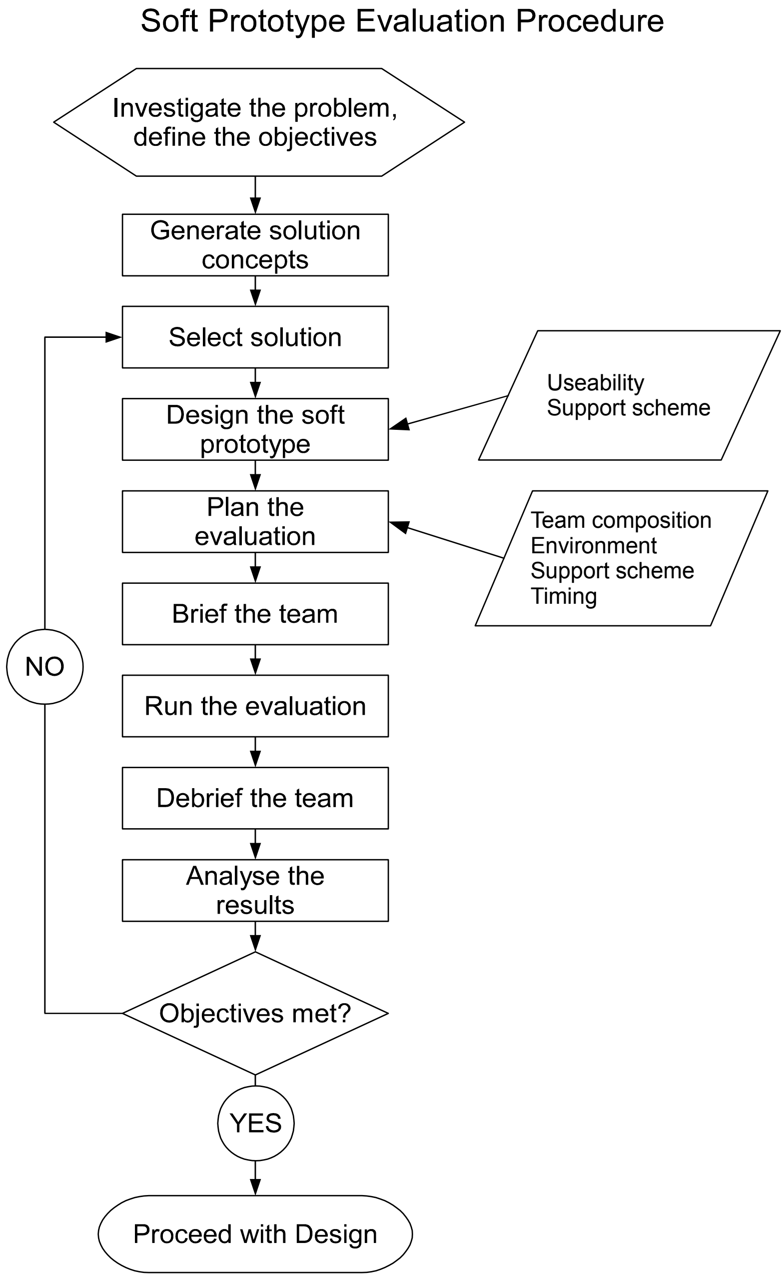

Figure 4-3: A flow chart of the process used in a soft prototyping evaluation.

be expert in all these aspects, but should be able to understand them, integrate them into an overall plan, and communicate the plan to the rest of the team. The team leader should be able to be decisive in a rapidly changing situation.

3. *Clinical specialist.* The clinical specialist is responsible for understanding the clinical need of the evaluator. In the case of a seating design project, this person is likely to be an occupational therapist. The clinical specialist will create a clinical specification, specifying where and what type of support should be provided. The clinical specialist should also be able to analyse the outcomes of the simulated intervention, and propose changes to the support scheme to be implemented by the designer (see below).

4. *Designer.* The designer is responsible for interpreting the clinical specification into an engineering concept to be simulated as a soft prototype. The designer should understand the specification provided by the clinical specialist, and propose technical concepts that are realistic and feasible. The designer should analyse the outcomes of the evaluation with the help of the clinical specialist, and appropriately modify the proposed support scheme.

5. *Advocate.* The advocate's role is to ensure that the interests of the evaluator are properly represented in the evaluation, especially where the evaluator finds communication difficult. This person should be someone who knows the evaluator well, and who is trusted by the evaluator. During the planning phase, the advocate should highlight aspects of the plan that are likely to cause difficulty for the evaluator, and should be able to propose modifications to the plan to mitigate them. During the evaluation the advocate should focus on maintaining awareness of the evaluator's state of mind and should be able to request a change to the plan or call a halt to the evaluation.

6. *Observer.* The observer's role is to observe the evaluation in a objective way, preferably without being involved in physically supporting the evaluator. This person should have an eye for detail, and should be able to observe the evaluator's response to the intervention. It is also the observer's role to operate the outcome recording equipment such as a video camera or sensors embedded in a semi-soft prototype. This is an important role that can yield information that can easily be missed by the other members of the evaluation team when they are concentrating on providing support.

7. *Supporter* There may be one or more supporters. These are the people who provide direct support to the evaluator during a soft prototype evaluation or who support the prototype in a semi-soft evaluation. It is critical that the supporters understand their role in the evaluation in detail. During the planning phase they should be able to point out difficulties with implementing a proposed support scheme because, for example, they may not be able to reach where asked or provide the necessary range of motion. They should be able to work together and closely coordinate their actions where necessary. They should have a good ability to interpret their support task into consistent physical support throughout the evaluation.

Each of these roles is important, but, depending on the scale and complexity of the evaluation, one person may fulfil more than one role. For example, the advocate and observer or clinical specialist and leader may combine roles.

4.4.2 Planning a Soft Prototype Evaluation

An evaluation should be planned carefully taking into account a number of factors which are described below. It can be helpful to ask the following questions to ensure that the evaluation is planned sufficiently:

1. *What is the concept being evaluated?* The objectives of the evaluation should be clearly identified. It should be possible to sketch the conceptual design of the proposed technology, or at least the location and function of each support provided. Each movement should be thought through, noting where coordination is required with other related movements.

2. *How will the concept be interpreted as a soft prototype?* Where is support to be provided, and what motion is necessary? Though it is not possible for a soft prototype to fully mimic a physical prototype (it is an interpretation of the yet-to-be-built physical device rather than a translation) the soft prototype support scheme and its associated patterns of coordinated motion should be designed to match the *evaluator's experience* of the concept as closely as possible. It is also important to consider the range of motion and comfort of each of the supporters, ensuring that they will be able to carry out their support task consistently for the duration of the evaluation.

   Two key limitations in the fidelity of a soft-prototype to the final device are:

   (a) **Reaction times:** The ability of supporters to react to the motion of the evaluator is limited by finite reaction times. For example, a human supporter cannot truly simulate a spring because there is a small delay between the supporter sensing the applied force and then reacting to it. This aspect should be taken into account when designing the soft prototype.

   (b) **Large support surfaces:** It is not possible for human supporters to provide large support surfaces without using props. If a large contact area is important, then a prop such as a support board may be needed.

3. *What is the likely emotional state of the evaluator?* Potential reactions of the evaluator to the people present and the proposed procedure should be taken into account when designing the evaluation plan. For example, a child may react negatively to a therapist who is associated in his mind with unpleasant seating experiences or uncomfortable physiotherapy. Though it may be essential that the therapist is present and involved in the evaluation, it may be helpful if she is positioned out of sight of the child during the evaluation procedure.

   Other steps may be taken to reduce the anxiety of a child including carrying out the evaluation in a calm and familiar environment, keeping noise levels to a minimum, speaking calmly and quietly, and providing suitable distraction for the child such as a favourite DVD or some other entertainment. Many children with neurological conditions such as cerebral palsy find coping with auditory and visual clutter difficult. Reducing clutter in an environment can increase the child's ability to concentrate and cope with a difficult evaluation.

4. *Who is needed to provide the support?* The members of the team should be carefully chosen. The author found that where two people needed to closely coordinate their movements, it was helpful if they had worked together before. It was also helpful to have a person present who was known and liked by the child (the advocate). This person provided some reassurance for the child and reduced anxiety. Therapists were assigned to positions where support with movement was required because of their familiarity with making consistent judgements about the qualities and extents of movement. Lastly, it was found helpful to have an observer present who did not have a support task and who was able to watch the evaluation using a roving video camera (in addition to a static camera) to capture specific details as they occurred.

5. *How will the outcomes of the evaluation be recorded?* The methods of capturing the outcomes of the evaluation should be planned. Likely observations and measurements will include judgements and possibly measurements of the quality, range and force of motion of the evaluator; the effect of varying simulated static and dynamic support parameters such as spring rate and damping; and the demeanor and communications of the evaluator during the evaluation. It is recommended that video and audio recording are used to capture not just the motion of the team and the evaluator, but also the conversations of the team and the communications from the evaluator that may be missed at the time. The placing of video cameras and an awareness of their placing by the team is important. The author found too often that important events were missed on video because of a team member kneeling or standing in front of the camera at a critical time, unaware that they are blocking its view of the evaluation. Brightly coloured self-adhesive tape may be placed on the floor to indicate a camera's field of view and reduce the number of camera obstructions.

   If available, motion capture technology may be used to provide high quality quantitative measurement of the evaluator's movement.

   The author have found that simply reviewing video of the evaluation immediately after the evaluation often yielded information that was not noticed at the time either because the camera could see what the support team could not, or more frequently because the team members were concentrating on providing an accurate support simulation and did not notice exactly what occurred.

4.4.3 Preparing for a Soft Prototype Evaluation

When planning is complete, it is important that the plan is communicated to the evaluation team accurately, and that the team can confirm that they understand what is required for the simulation and evaluation of the support concept to be useful. The utility of the concept evaluation depends upon the coordination of the team's movements.

1. The evaluation team leader should plan the evaluation, taking into account multiple factors such as the likely emotional state of the child and and the safety of the evaluation team.

2. The evaluation team leader should ensure that the objective of the evaluation is clearly explained and understood by the entire team.

3. The evaluation team leader should also ensure that the concept being evaluated is also understood by each team member. This is so that they are able to interpret their role in the support scheme into a support design as accurately as possible. A failure to ensure this understanding may result in a lack of coordination between team members, and support that is inconsistent with the concept being evaluated.

4. The evaluation team leader should ensure that each team member understands their specific role in detail, and in particular that they understand how they should coordinate with other team members who are simulating part of a support mechanism to which their own part is 'connected'.

5. The team should practice working together before the child is introduced into the situation. Practicing the simulation enables the team members to check that they can provide the support needed, that they have a sufficient range of comfortable movement themselves to cover their task, and that they are able to coordinate their movements together as required.

6. Finally, the team leader should ensure that all necessary preparations are complete before bringing the child into the evaluation room, and that the team members understand their roles and are ready to begin.

4.4.4 Running a Soft Prototype Evaluation

Evaluating soft prototypes is most effective when planned carefully, but can still yield useful information when used much more spontaneously. However there is a risk that an ill timed or poorly executed evaluation can prejudice a child against future involvement with the team.

When planning and practice is complete and the team are ready, it is time to bring the child into the room and begin the evaluation. If it is the first time that a particular child is being asked to evaluate a soft prototype, then it may be worthwhile meeting the child on a separate occasion prior to the evaluation so that the child is not presented with a large group of strangers asking the child to do something he or she is not used to doing.

The following guidelines are offered from the author's own experience of conducting soft prototype evaluations:

1. *If possible, introduce the evaluator to the evaluation team prior to the evaluation.* This can reduce anxiety and lead to a calmer and more productive evaluation session.

2. *Be flexible in the running of the evaluation.* The author has found that sometimes an unexpected finding leads the evaluation in a different direction to that originally planned. It is here that the prior integration of the team is important. If the team understand the overall evaluation objectives, and are fluent working together; then adapting the planned programme to take account of changed circumstances or a modified goal is unlikely to be a problem.

3. *Be prepared to abandon an evaluation session at short notice.* The advocate's role is to represent the interests of the evaluator during the evaluation. This may mean on occasions that the evaluation needs to be abruptly terminated if the evaluator is becoming distressed for example. It is better to terminate the evaluation quickly, remove the evaluator from the situation, and retain the trust and goodwill of the child for another day, rather than press on with an evaluation that may yield little more (poor quality) data on that day. To continue in these circumstances will ultimately be counter-productive and prejudice the evaluator against further work with the team.

4.4.5 A Paediatric Case Study[7]

This case study illustrates how soft prototyping can be applied, particularly where multiple concepts need to be explored, and where the evaluator is anxious about the equipment that needs to be evaluated. This evaluation was carried out very early in the process of developing these techniques, and as a result it was more spontaneous in its design and execution than is recommended now. It does however illustrate the effectiveness and benefit of using soft prototyping methods.

Child R1 evaluated a dynamic seat designed to yield when a spasm occurred, allowing the child to remain properly seated in the seat without applying large forces to the pelvis. The seat concept to be evaluated featured a static base, a dynamic backrest with a head support and a dynamic footrest. See Figure 4-4

The first hardware evaluation was carefully planned. The evaluation was held in the child's school hall, which was quiet and well lit. The team present were R1's physiotherapist, the research engineer and two research occupational therapists. After the chair had been set up, R1 was brought into the room by his mother and shown the chair. Its workings were explained to him and his mother carefully, as it was thought that the more he knew about the chair and his role in evaluating it, the less anxious he would be about what his experience of the chair would be like. This assumption proved to be incorrect.

During the discussion it became clear that R1 and his mother were becoming more and more anxious, and that the anxiety of one was reinforcing the anxiety of the other. Having checked with R1's mother that she was still content to proceed, the evaluation team decided to commence the evaluation before R1's anxiety became any worse. He was secured into the seat with a pelvic belt, foot straps, thoracic lateral supports and a chest strap, and immediately began to experience alternating whole body flexor and extensor spasms at a frequency of about one hertz. He became distressed, and the evaluation was abandoned after only twenty seconds. R1 was removed from the seat, reassured that he would not be using the seat any more that day, and taken back to his classroom. The team reviewed the evaluation, considering how the seat could be evaluated more successfully in the future, and questioning whether its fundamental principles of operation were still valid.

It was thought that the principle of incorporating compliance into a seat was beneficial, as R1's mother allowed him to move when she was holding him, and previous work by the author and others [26, 7, 5] had provided evidence that this was likely to be so. The movement seemed to enable him to be held comfortably, and was to be preferred to his experience when constrained into a rigid seat. For this reason the team decided, with R1's mother, to visit him at his home and assess the validity of the principles of the seat without using the seat itself.

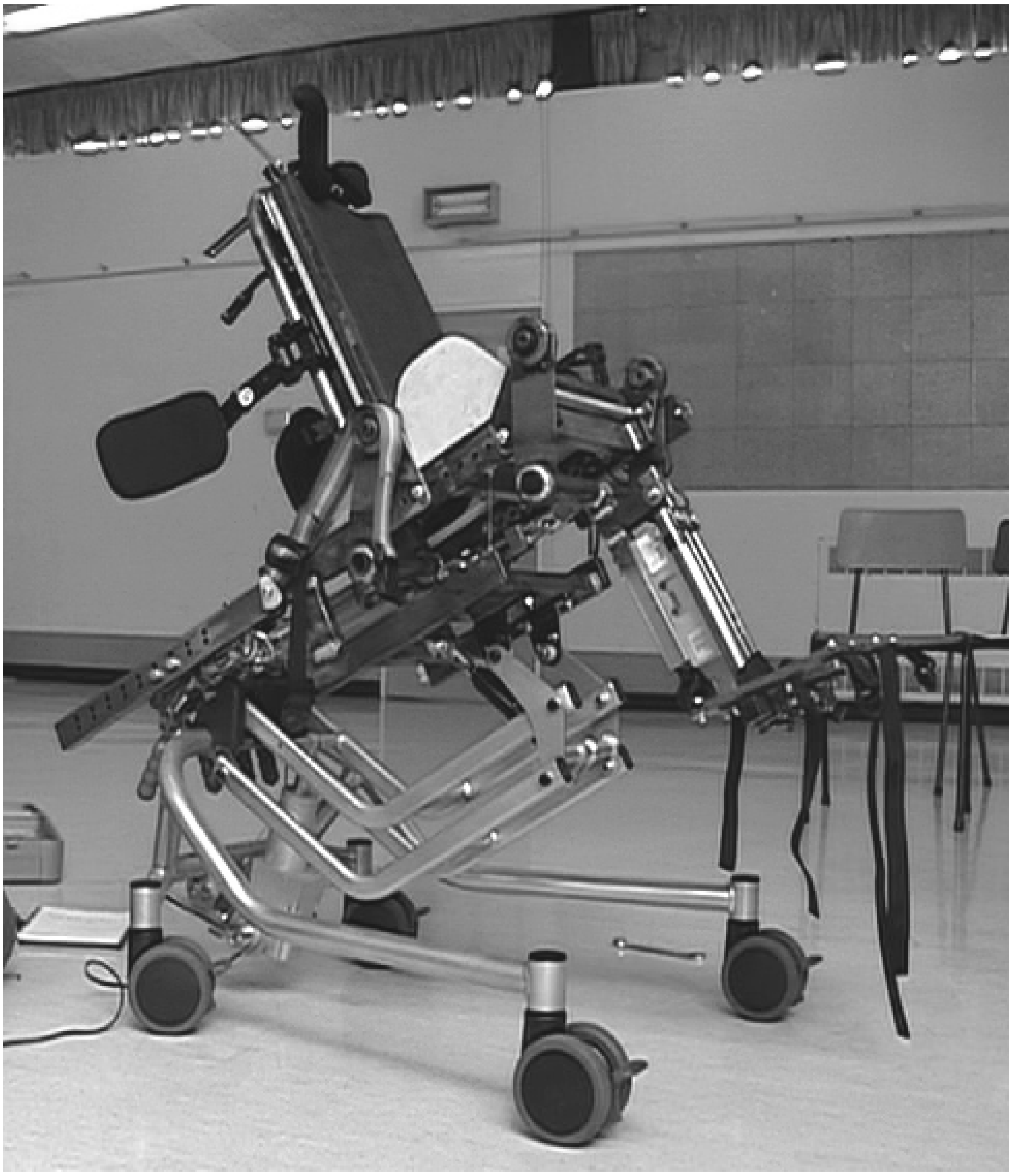

Figure 4-4: A photograph of R1's first dynamic seat. After the first hardware evaluation was curtailed because he became distressed, this seat concept and others were evaluated as soft prototypes in his home.

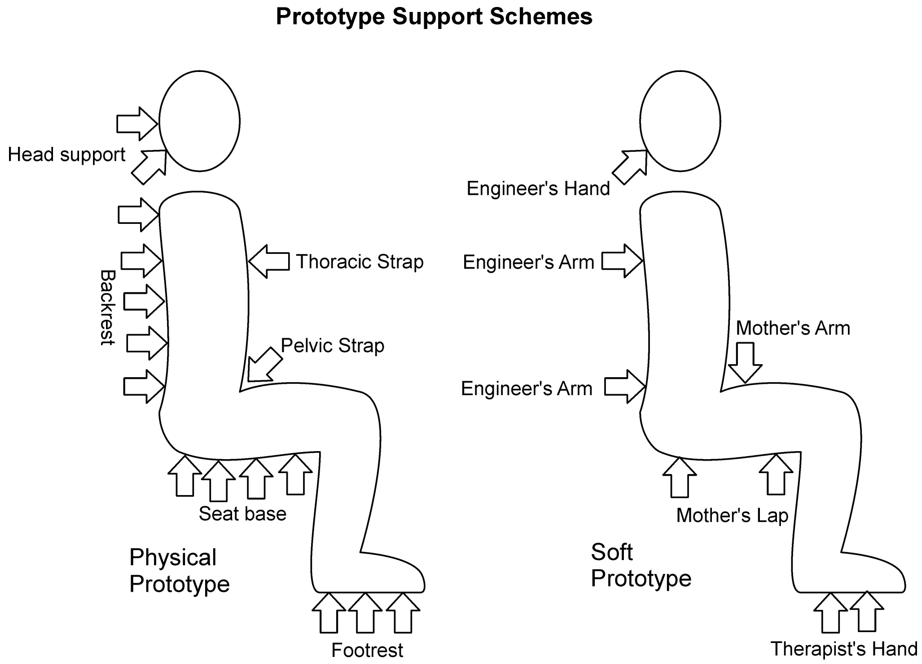

Figure 4-5: A diagram showing and comparing the support provided by the physical seat with the support provided during the soft prototype evaluation. The arrows indicate where support was provided for each prototype. The reduced support in the soft prototype is provided by the hands, arms and lap of the supporters.

At home, R1 was relaxed and calm, as were his mother and grandmother. The team introduced themselves to R1 once again and explained to him and his mother what they were planning to do: that they wanted to try to understand more about how his mother supported him, and to try out a pretend seat for him which they would make from their hands. The engineer explained to the occupational therapist and R1's mother exactly what he wanted them to do while R1 was supported on his mother's lap.

The team aimed to simulate the seat that was tested that morning by positioning R1 sitting across his mother's lap, with his mother securing his upper thighs and lower sacrum with her hands. The occupational therapist knelt in front of R1 and held each of his feet in her hands. The engineer positioned himself in front and to one side of R1's mother, and supported R1's back with one hand and his head with the other. Clearly this is not exactly the same support that was provided by the seat, but it was felt to be a close enough analogue to reality to be useful. The team also attempted to simulate the dynamic properties of the seat mechanism, adjusting their responses to R1's movements to simulate the spring and damping forces applied by the seat. The physical and soft support schemes are compared in Figure 4-5.

The evaluation proceeded. R1's response to the simulated seat was similar to his response to the physical seat during that morning's evaluation in his school, but with far less anxiety and upset. As a result, his spasm frequency and spasm duration were reduced. His mother had previously reported that his spasm frequency and intensity were reduced when he was calm and relaxed, compared to an increased frequency and intensity if he was excited or distressed about something. The evaluation confirmed aspects of the design of the seat, but also revealed some of its limitations, particularly that the mechanical link between the backrest assembly and the footrests enabled R1 to bridge across these two components during a spasm and provided him with a means of pushing powerfully against his pelvic strap. Having observed this effect, the evaluation team began to use the evaluation of soft prototypes to explore alternative means of supporting R1 that would reduce the external forces applied to his pelvis, evolving and testing concepts rapidly during the afternoon session and in other later sessions with R1 and A1. These concepts were incorporated into a semi-soft prototype that was evaluated several months later.

4.5 Semi-soft Prototyping

Semi-soft prototyping is a tool for approximately determining the dynamic mechanical specification of a complex support system, through the use of a minimally functioning prototype operated by a team according to a predefined rule set. The method was developed as a way of reducing the risk of designing and building complex prototypes that would then prove to be unsuitable.

A semi-soft prototype is functional kinematically. It provides a degree of support to its occupant whilst deriving its dynamic properties from its team of human operators. A semi-soft prototype is an incomplete prototype used to assist in the determination of the desired dynamic properties of a system. It enables the assessment of the human response to changes in the quality of the dynamic support, without the design and construction of a dynamic system. For example, in this work, a semi-soft prototype was used to determine the viability of the independent seat concept (See Section 9.3). A simple hinged prototype was built, based upon the outcomes of the previous soft prototype evaluation described in Sections 8.1.2, 9.1 and 9.2. This semi-soft prototype was a ‘floppy’ hinged support that could not hold itself or its user in any position. For example, the backrest was hinged at its base, but did not have any springs or dampers to control its motion.

Semi-soft prototyping is a similar process to that used for soft prototyping, however the evaluation team coordinate their movement with a moveable device interposed between their hands and the evaluator. This interposition makes the evaluation more challenging, as the physical feedback from the child to the evaluation team will be muted and modified by the prototype structure and mechanism. The composition of the evaluation team will be similar to that described in Section 4.4, and similar issues should be considered when determining the composition of the team.

4.5.1 Designing for Semi-Soft Evaluation

A semi-soft evaluation is significantly different to a soft prototype evaluation in that it employs a physical prototype. This prototype must be designed and built before the evaluation can begin. It must embody the kinematics of the seating concept while allowing exploration of the dynamic aspects of the support scheme. It is not just a ‘floppy’ partially constrained version of the final concept, as it will be controlled by human operators. The inclusion of affordances for human interaction with the prototype by the evaluator and the team who are operating it should be considered to be integral to its design. The semi-soft prototype *includes* the team providing its dynamic features, and the physical component of

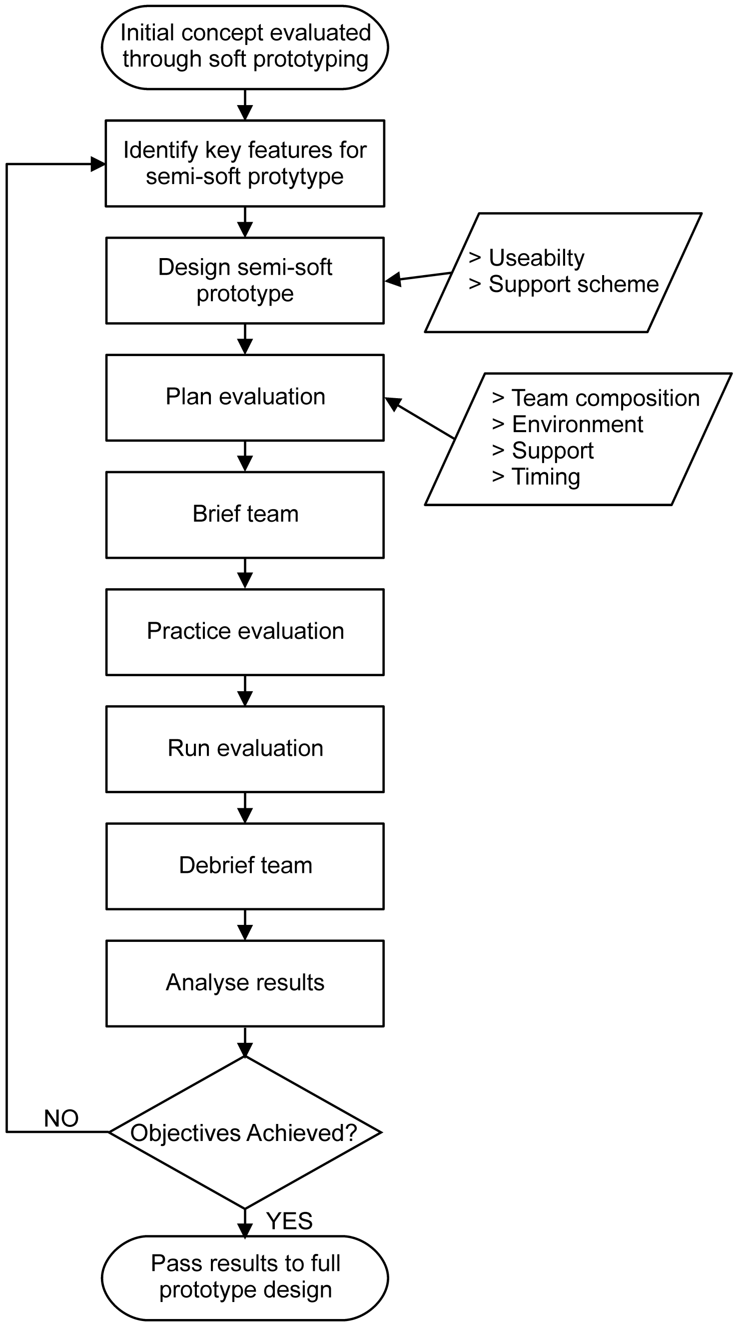

Figure 4-6: A flow chart of the semi-soft prototype evaluation process.

the semi-soft prototype should be designed with their positions, hand holds, and range of movement in mind. For example, the designer should be careful to avoid finger traps for seat operators as well as the person sitting in the prototypical seat. The following list of considerations will provide the designer with some useful guidance:

1. *The semi-soft prototype consists of two components:* These are the physical device and its human operators. These two components are intimately connected when the prototype is being evaluated, and they cannot be considered, selected or designed in isolation from each other. The designer of the physical semi-soft prototype must consider how the evaluation team will interact with it.

2. *Consider where the boundary lies between the physical and the human components:* A critical decision to be made early on in the design of the semi-soft prototype is the boundary between what is embodied in the physical prototype and what is to be simulated by the operators. The author has defined this boundary by considering the capabilities of the evaluation team, and by aiming to make the design of the physical prototype as simple as possible. For example, when designing a complex dynamic seat, the footrests were simulated entirely by the evaluators because the child's shoes could be held securely by an evaluator's hand and the experience of the child would be little different had the shoes been held by foot rest straps. Conversely, the backrest was built in some detail, incorporating lateral supports and a back plate and cushion. This was because it was difficult for the evaluators to provide the same degree of support along the length of the back that a backrest would provide, without crowding too many people around the prototype and posing a serious movement coordination challenge.

3. *Design for the positions of the operators:* Ensuring that there is room for all the operators to fit around the prototype is not necessarily straight forward. The position and function of each operator should be integral to the design of the physical prototype.

4. *Design safe and comfortable handholds for the operators:* The designer should ensure that there are safe and comfortable handholds on the physical prototype for the operators to use. The hand holds do not need to be complex or over-engineered for comfort, but they should be free of finger traps and pinch points, and they should be comfortable to hold for the planned duration of the evaluation.

5. *Consider how the evaluation will be recorded and observed:* How will the evaluation outcomes be recorded? It *may* be helpful to build some instrumentation into the semi-soft prototype that will provide quantitative data on how the operators and the primary evaluator interacted with the physical prototype. In the end, the designer of the fully functional independent prototype needs the specification of the device to be described in numbers that quantify angles, forces, moments, ranges of motion and so on. These parameters can be usefully captured with simple sensors such as load cells and electromagnetic angle sensors. The designer should bear in mind, however, that the semi-soft prototype is an early stage device, and part of its reason for existing is that it enables experience of the concept to be gained quickly. Thus it is important not to spend too much time building complicated sensor suites into the prototype, when careful observation and video recording may provide sufficient information.

4.5.2 Planning a Semi-Soft Evaluation

The process of planning a semi-soft prototype evaluation is similar to the process outlined above in Section 4.4.2, with additional considerations around the physical semisoft prototype.

In a semi-soft prototype evaluation, the evaluation team leader should once again ensure that the team members understand the mechanical principles being embodied in their human assisted system - the supporters in particular should understand the mechanism they are simulating, in terms of how it interacts with the evaluator. This is so that they can accurately reproduce the mechanical properties of the seat being simulated. The ability of the supporters to simulate a mechanism is one of the main limitations of the soft and semi-soft prototyping processes, along with the ability of the supporters to provide support that accurately reproduces that provided by the concept being evaluated. For example, supporter reaction times limit the responsiveness of a system to movements rapidly initiated by an evaluator. If an evaluator is very sensitive to resistive forces applied very soon after a spasm initiation, then this limitation may pose a significant problem.

It is important that *all* the support team members understand *all* of the seat mechanism, as different movements may need to be coordinated. A full understanding of the simulation by all the team members will allow them to accommodate one another and react to unexpected responses by the evaluator in a coordinated and consistent way.

4.5.3 Semi-soft Prototyping: A Case Study

During the soft prototype evaluation described in Section 4.4.5, two concepts were evaluated. The first, shown in the section referred to above, was a retrospective evaluation of a seat concept that had already been built. This was carried out because of the child's negative emotional reaction to seating and especially new seating. This evaluation enabled an existing design to be confirmed.

The second evaluation carried out on that day was of an unbuilt concept - a fully independent dynamic seat (Chapters 9 and 10). The evaluation was designed to enable a decision to made as to whether the new seat concept should be pursued further, or dropped in favour of the more conventional linked seat approach already in progress. This second evaluation confirmed the potential of fully independent dynamic seating and work to develop it further was initiated. Development of the linked seat(Chapter 7) was suspended.

A semi-soft prototype of the fully independent seat was used to reduce the unknowns around its design and configuration, without the need to build a complex, time consuming and costly prototype. This prototype reduced (but did not eliminate) the risk of failure of the full prototype.

A simple prototype seat was built, based on the concept tested in the soft evaluation. This semi-soft prototype was intentionally only partially functional. It was designed and built quickly and at low cost from components already available in the workshop. Its dynamic components were simply hinged and otherwise unconstrained, hanging down from the seat if not held in place by an operator: it was for this reason that it became known as the 'Floppy Seat'. It was a rough and ready prototype, but it embodied the essential geometry of the new concept, and with a team of operators, it became a fully functional dynamic seat.

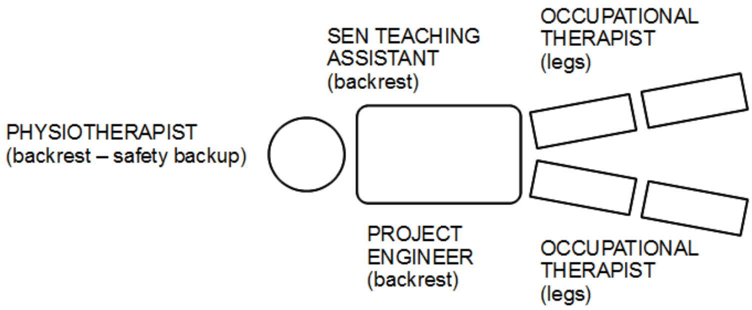

Figure 4-7: A diagram of how the evaluation team was arranged around the semi-soft prototype.

The evaluation team was assembled in the therapy room of R1's school, to plan and prepare for the evaluation. The diverse team comprised:

1. R1 – Seated (Evaluator) – not present for planning;
2. Engineer – Back support (Team Leader / Designer / Supporter);
3. Occupational Therapist – Foot support (Clinical Specialist / Supporter);
4. Occupational Therapist – Foot support (Supporter);
5. Physiotherapist – Safety back support (Supporter);
6. Teaching Assistant – Back support (Supporter);
7. Therapy Assistant – Camera operator (Observer);
8. Class Teacher – Pastoral support for R1 (Advocate).

The evaluation was planned in detail in R1's absence. Previous experiences had shown that he would be less distressed if brought in for the evaluation at the last minute. Planning included the location of the evaluation, how the team would support the semi-soft prototype, and how R1 (the evaluator) would be introduced to the evaluation team. The evaluation was planned to occur in the school sensory room, with low lighting and a favourite 'Bob the Builder' DVD being shown on a big screen. The evaluation positions of the team were planned carefully. R1's physiotherapist, with whom he did not have a good relationship, was positioned behind the prototype out of R1's line of sight so that her presence would not increase his anxiety during the evaluation. It was important that she was present, as she needed to observe R1 in the seat.

The team were positioned around the soft prototype, with five members in fixed locations operating the seat (the supporters), and the advocate and observer being free to move around. The advocate role was filled by R1's teacher. The team practiced the evaluation once. The team leader was making some adjustments to the seat when R1 was brought into the room prematurely. Communication from the team leader to R1's teaching assistant had been inadequate and she brought him in when she thought best, rather than when the evaluation team was ready.

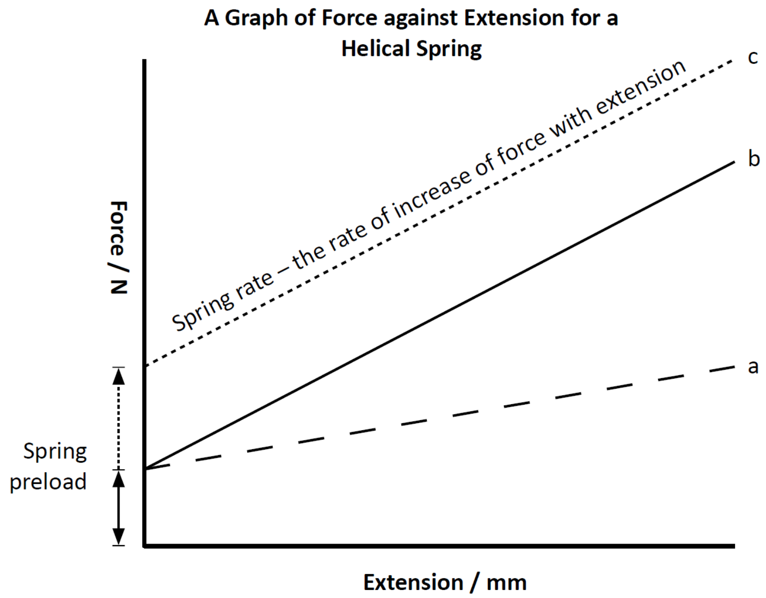

Figure 4-8: A sketch graph of the characteristic for helical wire-wound extension springs, showing the spring rate and force threshold adjustments that could be made with the seat, and simulated with the semi-soft prototype. When the springs are incorporated into the seat, the preload (varies between lines *b* and *c*) is the initial force required to start the footrest or backrest moving. The spring rate (varies between lines *a* and *b*) defines how quickly the opposing force increases as the seat back or footrest is deflected by the user.

To prevent R1 having to endure further disruption and risk him becoming distressed, now that he knew an evaluation was planned for him, the team leader decided to go ahead with the evaluation immediately rather than transfer the whole team and the prototype to the sensory room with R1 present.

The supporters took their places, R1 was placed in the seat by his teaching assistant, and the lap-strap was fastened. The evaluation was begun and recorded on video by the observer. See Figure 4-7.

Several different dynamic characteristics were evaluated. The list below gives examples of the kinds of parameters that can be evaluated using semi-soft prototyping.

1. *Spring rate:* Two different spring rates were evaluated. They are sketched in Figure 4-8. Varying the spring rate changes how quickly the opposing force/torque of the backrest or footrest rises as it is displaced. The greater the spring rate, the greater the ability of the seat to oppose the occupant's spasms. The seat operators were asked to vary the rate at which they increased their resistance as the spasms displaced the backrest in a series of trials. See Figure 4-8.

   R1 responded differently to the two dynamic configurations tried during the evaluation, with his spasm force being higher when the simulated spring rate was increased.

2. *Backrest preload:* The effect of varying the preload of the springs on the backrest was evaluated. Preload on the backrest springs creates a threshold torque which must be overcome before the backrest will move. This was thought to create a feeling of security in the seat when it is in normal use. However, if the preload is set too high, then the seat no longer feels compliant to the

user, and much of its effect is lost.

3. *Foot support / back support preload bias:* The effect of varying the ratio between the preload on the backrest and leg support 'springs' was investigated. R1 seemed less disrupted by leg movement than by backrest movement, so the leg support 'springs' were made weaker than the backrest springs.

When initially sat in the seat, R1 seemed unsure about it and became a little distressed, however once seated securely he quickly settled and seemed to enjoy the movement, even smiling during the evaluation.

4.6 Outcomes

There were several outcomes and conclusions drawn from the evaluations, relating to R1's spasm characteristics while seated, and the implications for the seat design that could be drawn from them.

The soft prototype evaluation of the first seat concept that had been evaluated for only twenty seconds in the first session showed that the seat concept was not fatally flawed, and that the environment and plan for the evaluation had contributed substantially to the child's difficulty with the seat. He sat well in the soft prototype seat, and did not become highly emotional, sitting calmly on his mother's lap at home. This evaluation demonstrated the importance of managing the child's emotional state through careful planning of the evaluation environment and the people present.

The soft prototype evaluation also resulted in the research taking a new direction with a novel seat concept. R1 benefitted from the new position with improved engagement with the adults around him. The soft prototype evaluation gave the team sufficient confidence in the suitability of the new concept that they accepted the risk of abandoning the original concept.

The semi-soft prototype evaluation that followed further reduced the risk associated with the new design to a level where the team were able to commence design of a new fully functional prototype, with useful guidance available to the designer on how the dynamic parameters of the new seat should be configured.

R1 sat well in the semi-soft prototype seat. He experienced a large number of spasms, but did not seem to be distressed. His posture and head control were good and the evaluation demonstrated that the tested seating principle was viable and should be followed up with a full scale independent seat prototype.

The time-line for the first seat concept was:

- **9 months** to design and build the first seat prototype
- **1 day** testing - prototype found to be unsuitable.

Had a soft prototype been used initially, important details about the first prototype would have been changed (the backrest would not have been linked to the leg supports, for example) and the seat would have been likely to be more successful.

To build a second prototype that may have worked would have taken a further nine months of design and build and then two months to evaluate. It is important to note that arranging time for evaluation with all the staff and family involved was not a trivial task, especially as the children recruited for this work were a considerable distance from the workplace of the engineer and occupational therapists. This complexity added to the extended periods of time between evaluations.

Working part-time, the engineer's and occupational therapists' time-line for the second prototype seat, including the soft and semi-soft prototypes, was:

- **1/2 day soft prototyping** - this confirmed that the new seat concept was likely to work and enabled further work to take place. Without this test it would have been considered too risky and would not have been attempted.
- **2 months further soft prototyping** - further soft prototyping was used to develop the concept of the seat further. Simple props were used to explore how the children should be supported, and thence derive the structure needed for the semi-soft prototype.
- **4 months design and build** - this time was used to design and build the semi soft prototype. This prototype was highly successful when evaluated and formed the basis for a subsequent full prototype.
- **2 months evaluation and concept generation** - this time was used to evaluate the semi-soft prototype with two children: R1 and one other. The evaluation showed that the seat concept was very likely to be successful.
- **8 months design and build** - The second seat prototype was designed and built, based on the findings from the soft and semi-soft evaluations. Evaluation of the fully independent seat was very successful for A1 and moderately successful for R1 (See Chapter 11).

4.7 Discussion - Reducing the Human Unknowns through Inclusion

Soft prototyping is not a substitute for the careful evaluation of fully functional prototypes, but it is a tool that can usefully extend a team's knowledge about the likely effectiveness of a given design. It can provide evidence for or against the effectiveness of a concept at a very early stage of the design process, enabling concept selection and fundamental design decisions to be made with greater certainty. The impact of design changes can be meaningfully assessed before implementing them in hardware. In the case studies described, the use of soft and semi-soft prototype evaluation enabled a new seat concept to be explored with only a small cost in time and resources if the exploration failed. If soft prototype evaluation had not been used, the concept would not have been explored as the project could not have afforded to risk losing the time and other resources within its fixed budget and timescales had the concept been unsuccessful.

Soft and semi-soft prototype evaluations are limited in their ability to accurately simulate an otherwise unbuilt device. They do not flawlessly reproduce the experience of a device from the user's point of view and so should not be used to assess the details and subtleties of a design. However, they should be used to assess broad design concepts, test new interface approaches and check changes to existing prototypes before building. Limitations referred to earlier in this article include supporter reaction times and the ability of the supporters to fully support large body surfaces during soft-prototype evaluation.

These methods are founded upon a thoroughly user-centric methodology that puts meaningful feedback from direct user experience at the start and the heart of the concept generation and design process. People with severe physical and cognitive disability are able to make meaningful contributions during the early stages of design and concept generation, rather than contributing only to the evaluation of already established concepts. The design of assistive technology will be more successful, faster and less risky if methods like soft and semi-soft prototype evaluation are applied throughout the process, rapidly reducing the human unknowns.

Chapter 5

Measurement and Assessment Strategy

A significant part of this research is the measurement of extensor spasms and the evaluation of novel seating designs. These measurements and observations have served three objectives of the research:

1. To provide an understanding of the medical context of each child participating in the research;
2. To develop a deeper understanding of extensor spasms in children;
3. And to provide a functional evaluation of the novel seat prototypes being designed within the context of the iterative design process.

The design of seating requires qualitative and quantitative information. The designer needs to know both *how* the user responds to the prototype, and the *scale* of the user's response. The engineer uses the qualitative data to design the function and engineering concept (for example, the geometry of the seat mechanism), and the quantitative data to determine the detailed aspects of the design; for example, the force required to be exerted by the main backrest spring and the dimensions of the mechanism geometry.

5.1 Initial Clinical Examination

Each child was assessed clinically at Great Ormond Street Hospital on admission to the project. The assessment was carried out in the spinal clinic and included a medical examination and a spinal x-ray. The child's sitting ability was also assessed at the clinic using the Chailey Sitting Ability Scale. Children were admitted to the project if they scored one on the scale; that is, they were unplaceable. Each assessment followed the procedure below:

1. **Spinal X-Ray:** The child's spine was x-rayed to check for spinal abnormalities such as scoliosis (twist), lordosis (backward curve) and kyphosis (forward curve). These skeletal abnormalities would have resulted in the child being excluded from the research.

2. **Sitting Assessment:** The child was assessed against the Chailey Sitting Ability Scale. This was to determine whether the seat will be suitable for the child, and whether the child is unplaceable according to the Chailey Criteria[43]. The research was aiming to design a seat for unplaceable children who could not comfortably sit in any other kind of seat.

The children were observed during their initial clinical assessment by the research occupational therapist. The ability of the child to sit, as well as the character of the child's movements were noted. The sessions were video recorded.

5.2 Observation

Observations were made by both the occupational therapists and the research engineer, each bringing their different skill sets to bear. Both types of data were of value to the research, and were complementary in the type of information they yielded to the researchers. The therapists, with their greater clinical understanding of posture and seating, and training in clinical observation, observed how the child was sitting, and were able to suggest how the seat might be changed or adjusted to achieve a better seated position for the child. The engineer, with his better understanding of mechanics and his training in techniques such as force resolution and free body diagrams was able to observe the mechanics of how the child was sitting and was supported, and convert the objectives of the therapists into structures, mechanisms, adjustments and modifications to the seat. This partnership between clinician and engineer is key to successful design. Inevitably, both engineer and therapist learn how the other works during such a partnership, and the boundaries between professional functions become blurred in time.

Other important observers were the school staff and families of the children. They brought their understanding of the children gained from many hours spent handling and interacting with them. They were able to distinguish between usual and unusual responses, and report on gradual qualitative changes during the longer evaluations which it was more difficult for the research team to observe.

5.3 Sensors

The strategy developed for this research used both instrumentation and clinical observation to assess the nature of the children's spasms and their response to the prototype seats. Sensor based instrumentation was employed to provide objective and detailed quantitative measurement of the spasms; and clinical observation, assisted by video recording, provided qualitative assessment of the child's response to the seating in terms of posture, function, comfort, and movement.

Specifically, a detailed force and trajectory of the spasm course was sought, including small transient features that may enable future seating systems to be more responsive to their users. It would be advantageous for a seat to be able to modify its dynamic response immediately before a spasm, reacting differently to spasms compared to volitional movements. For this reason a high resolution (12bit / 4096 levels) and high sampling frequency was used (200Hz); thus the sampling frequency was based on the requirement to be able to detect very rapid muscle twitches.

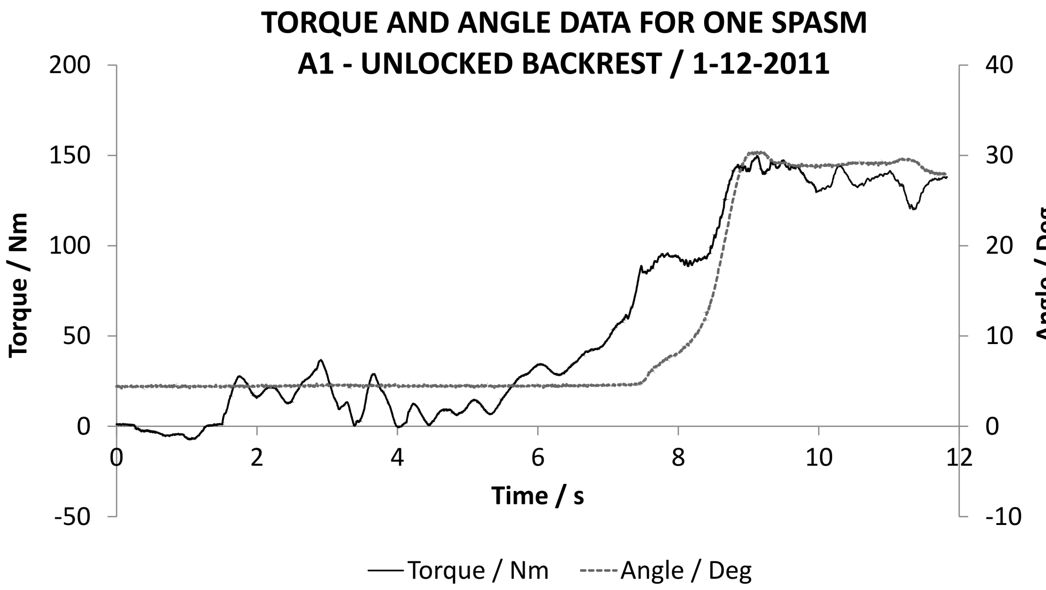

Figure 5-1: A graph of backrest torque and angle showing the fine detail of the torque measurement and the smoother angle data. The inertia and friction of the backrest mechanism smooths the angle data, while the preload on the spring eliminates any response to variations in the applied torque below the preload threshold. This data is from Child A1 during the December 1st 2011 evaluation.

Benz[50] measured extensor (and flexor) spasms resulting from spinal injury using electromyography (EMG) and a motion capture system. She sampled motion data at 100Hz and electrical muscle activity at 1000Hz. The high frequency of the EMG sampling was necessary to capture details of the muscle activity which were needed for her research. 100Hz sampling on the movement was sufficient because of inertial damping of movement moderating the response of the body to the applied muscle forces. High frequency muscle activity features would not be seen in the motion.

The sampling frequency employed on the dynamic seat (200Hz) was higher than the motion sampling rate on the Benz paper because the seat was measuring force and not just movement. Forces are not subject to inertial damping as no motion is required for force transmission. Though the viscoelastic properties of human tissue will reduce the magnitude of measured forces while tissue is compressing at the beginning of a spasm, some force will still be transmitted to the sensors. The fine detail of the force measurement was seen in the recorded data when compared to the motion data from the seat position sensors. See Figure 5-1.

If a 5ms muscle twitch feature is to be covered by at least two sampling points, then the time between samples must be less than half the duration of the feature to be detected, resulting in a time period between samples of 2.5ms. This equates to a sampling frequency of 200Hz. The data logger chosen[51] is capable of measuring across eight channels at 200Hz per channel. It has a single sampling rate across all channels, so motion was also sampled at 200Hz, though 100Hz would have been sufficient. A summary of the sensor specification for the first linked seat is shown in Table 5.1.

Ideally, detection of rapid transient muscle activity features would be achieved using electromyography (EMG) to directly measure the electrical activity of the muscles. Had this technique been used, it

Parameter	Levels	Resolution	Sampling Frequency
Footrest Angle	4096 levels, 90°	0.02°	200Hz
Backrest Angle	4096 levels, 90°	0.02°	200Hz
Top of Backrest Force	4096 levels, 75kg	0.18N	200Hz
Bottom of Backrest Force	4096 levels, 75kg	0.18N	200Hz
Footrest Force	4096 levels, 75kg	0.18N	200Hz

Table 5.1: A table showing the specification of the sensors used in the first dynamic seat. Subsequent seats used similar sensors, but in a modified configuration. See Table 5.2.

would have allowed measurement of the spasms in much finer detail than was possible with the indirect force measurement method that was used with the seat. However, placing electrodes on the child and setting up EMG equipment would have added too much complexity to the measurement task and placed too great a demand on the child, who was already stressed and in some cases distressed by the seat evaluation process. It was decided that spasms should be measured mechanically using force and position sensing. To protect the sensitivity of the force sensors (the load cells), the parts of the seat between the load cells and the occupant were designed to have a low inertia, within the constraints of manufacturing and design for a prototype, and lightweight materials and sections were used where possible.

The second full seat prototype (Chapter 10) used a similar instrumentation scheme and the same sensors. The main difference was that additional angle channels were required for the independent leg movement, and one of the backrest force channels was moved to a thigh. Its measurement specification is shown in Table 5.2.

The second independent seat used a similar instrumentation scheme to the first, however the angle sensors on the hips and backrest were changed as it was not possible to mount the Gill blade sensors when using the virtual hinge backrest and leg supports. The Gill sensors were retained on the knee joints. Specifically the leg support angles were measured

Further technical descriptions of the instrumentation systems for each of the three instrumented seat prototypes are given in Chapters 7, 10 and 14.

Parameter	Levels	Resolution	Sampling Frequency
Left Hip Angle	4096 levels, 90°	0.02°	200Hz
Right Hip Angle	4096 levels, 90°	0.02°	200Hz
Left Knee Angle	4096 levels, 90°	0.02°	200Hz
Right Knee Angle	4096 levels, 90°	0.02°	200Hz
Backrest Angle	4096 levels, 90°	0.02°	200Hz
Left Hip Force	4096 levels, 75kg	0.18N	200Hz
Right Hip Force	4096 levels, 75kg	0.18N	200Hz
Backrest Force	4096 levels, 75kg	0.18N	200Hz

Table 5.2: A table showing the specification of the sensors used in the fully independent dynamic seat. On this seat, seven channels were used rather than five as on the previous seat.

Part III

Exploratory Research

Chapter 6

Previous Work: Compliant Seating for a Child with Whole Body Extensor Spasms (2006-08)

6.1 Outline

A clinical referral was undertaken in 2006 to design a seat for an individual child with cerebral palsy and whole body extensor spasms. He was diagnosed with dystonic cerebral palsy and epilepsy. He was not able to be successfully seated in a rigid seating system and was unplaceable in a sitting position. He was assessed at Chailey Sitting Ability Level 1 / Gross Motor Function Scale Level 5. In this document he is known as Child T1.

T1 was assessed at an orthopaedic clinic at Great Ormond Street Hospital. His spasms were observed and his dimensions and a spinal x-ray were recorded. Following his referral, design of a seat was started. His assessment suggested that he sat more symmetrically with his legs abducted, and a decision was taken at an early stage to seat him on a saddle type seat. A prototype seat was designed at BIME and evaluated by him at the hospital. The first evaluation was successful and T1 sat in the seat for 45 minutes.

The design was revised and a second seat was built, based upon the dimensions and design of the previous prototype. This seat was evaluated for a short period by the child at his school and at his home prior to a set of final modifications, and subsequent delivery to his home where it remained in use for an extended period until he grew out of it.

6.2 Seat design

This seat was designed specifically for T1, and was based upon an assessment by the project occupational therapist. Seating him on a saddle seat in an abducted position (with his legs slightly apart) was more comfortable for him, and also seemed to reduce the intensity of his spasms. This effect was not measured objectively, but was observed by the occupational therapist. For these reasons his compliant seat was also designed with a saddle seat. It employed a dynamic backrest and a pair of dynamic foot supports, each of which was linked to the backrest through a mechanism under the seat. The foot supports were hinged about the knee joint rotation centre. Their rotational axes were not coaxial as the child's knees were abducted. A photograph of the the seat is shown in Figure 6-1.

The seat was initially fitted with novel thoracic lateral supports that were made from a compliant polycarbonate sheet. They provided security for the child, preventing him from falling forwards; but also allowed him limited movement. During the first evaluation they were found to support the child inadequately and were changed for rigid off-the-shelf lateral thoracic supports from the 'Stealth' company.

Initially the head support was made from the posterior half of a neck collar mounted on a steel frame fitted to the backrest of the seat. This was found to be highly successful for this child. It provided stability for his head while he was at rest, but during a spasm its flexibility allowed his head to move.

Subsequently a Stealth i2i[52] head support was used. It provided support to the head with a long pad that wraps around the back of the head, then forwards over both shoulders and down over the chest. It is difficult for a child with extensor or flexor spasms to be displaced from this support during a spasm or volitional movements, and it provides excellent support and stability.

A pelvic strap was used to secure the child in place on the seat. It was positioned so that it applied downward and backward force to the child's pelvis at an angle of 45° from the horizontal.

The child's feet were fixed to the footrests using a system of two straps and a heel cup. The straps originated either side of his toes, and crossed over to his heel, fastening his foot into the heel cup. This arrangement is shown in Figure 6-2.

It was found that when the child was not experiencing a spasm, his hips were abducting further due to the effects of his positioning and gravity. To counteract this movement and maintain his hip positioning, hip supports were designed that laterally constrained his thighs and maintained his position on the saddle seat. These supports were manufactured from polycarbonate sheet and were not fully rigid.

The seat mechanism was designed to be inside the saddle. It had the following main features, which are sketched in Figure 6-3:

1. A hinged backrest, pivoted beneath the hip joint inside the saddle.
2. Foot supports mounted on tubes hinged at the knee. The hinges were inside the saddle.
3. Two links between the backrest and each of the footrest mechanisms. These links could be adjusted in length to change the initial angular relationship between the backrest and footrests.
4. A compression spring between the backrest mechanism and the front of the saddle. Initially a conventional wire wound coil spring was used, however it was found that the creaking sounds it made during use were too noisy and startled the occupant. A gas spring was substituted.

Since its manufacture, a static seat with a similar saddle seat configuration has become commercially

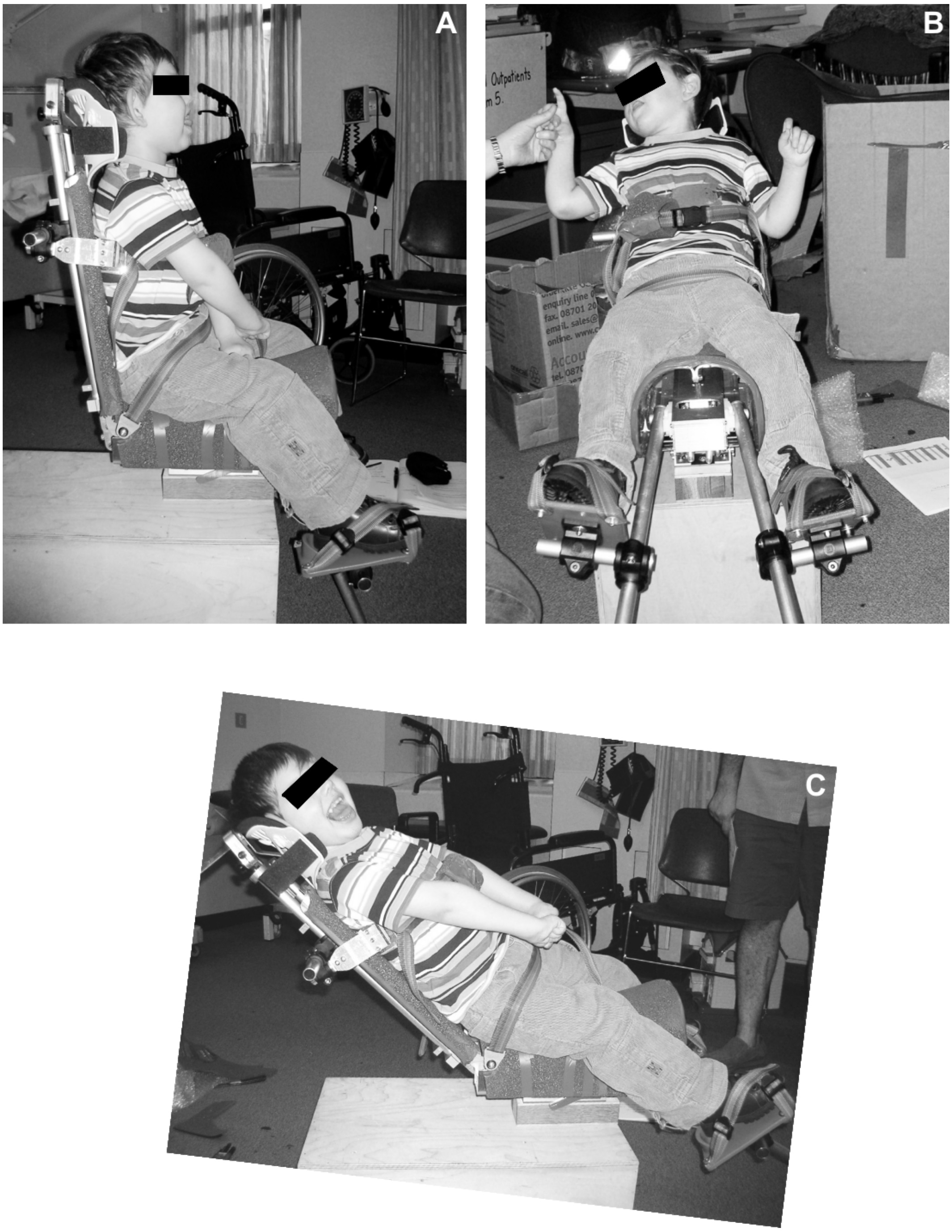

Figure 6-1: Three views of T1 in the prototype seat. The available range of motion can be seen. View C is rotated so that the seat in the picture is aligned horizontally like the seat in View A. The non-coaxial foot supports can be clearly seen in View B, as can the saddle seat configuration.

Figure 6-2: A photograph of the foot support on T1's seat, showing the crossed webbing straps running from toe to heel.

available from a Norwegian company. This is the Krabat Jockey[53]. No documented evaluation of this seat could be found in the literature or on the Internet.

6.3 Evaluation

Two prototypes were made during this design process. They were both of a similar design with evolutionary changes between them, particularly in the auxiliary supports such as the lateral thoracic supports.

The first prototype (Figure 6-1) was manufactured at BIME and evaluated at Great Ormond Street Hospital in a clinic room in the physiotherapy department. The prototype was mounted on a wooden box and T1 was secured in the seat. Initially he moved backwards and forwards in the seat rapidly, but as time progressed he began to gain control of the seat, positioning the backrest where he wished. Key observations from this forty five minute evaluation were:

1. **Postural control:** T1 quickly learned to position the backrest where he wished, and enjoyed moving the seat. He selected a slightly extended position for sitting.

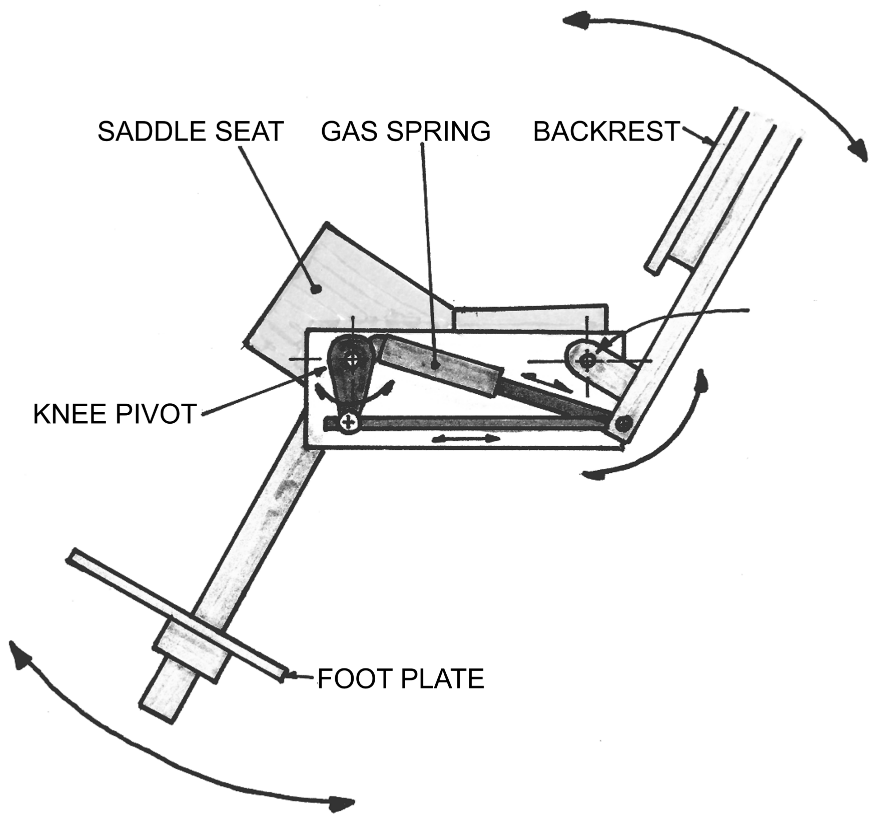

Figure 6-3: A sketch of the seat mechanism used on the seat supplied to a child under a referral to BIME before the generic seat research project. The sketch shows the supports, pivot points and mechanism built into the seat.

2. **Head control:** T1's head control improved. He was better able to maintain an upright head position while sat in the dynamic seat.

3. **Muscle tone:** There was an overall reduction in T1's tone. The research team watched his postural symmetry improve over about ten minutes.

4. **Hand function:** T1's hand function improved while in the seat. It was evaluated by observing him engaging in a fine motor activity at a table. This may have been due to his tone reduction no longer 'locking' his arm and hand movements.

5. **Spasm induction by startle:** The coil spring in the seat mechanism creaked when it operated. This noise was sufficient to induce spasms in T1, and the spring was substituted for a gas spring in the final seat.

The second seat (Figure 6-4) was strongly based upon the prototype and shared many of its components. The following major changes were made:

1. **Coil spring:** The creaky coil spring in the prototype was substituted for a silent gas spring. The easy adjustability of preload on the coil spring was lost. The gas spring pressure was only reducible by venting gas.

2. **Head support:** The neck brace head support was substituted for the more robust and cleanable Stealth i2i support (Figure 10-6).

3. **Lateral thoracic supports:** The polycarbonate thoracic supports were substituted for bought-in Stealth lateral supports, which, like the head support, were easily adjustable, robust and easy to clean.

4. **Lateral hip supports:** Hip supports were added to the seat to maintain pelvic symmetry on the saddle seat. T1 had a tendency to move to one side on the seat. This was probably due to asymmetry in his hip extensor spasm pattern.

5. **Base:** The wooden box was substituted for a bought-in mobile and height adjustable base suitable for home and classroom use.

Figure 6-4: Child T1 at home using his dynamic seat.

Chapter 7

Design of a Linked Dynamic Seat

This chapter describes the design of the first prototype generic seat. It was designed to fit the dimensions of the child recruited to the project at the time, who was coded within the project as R1.

7.1 Design Rationale

The aim of the generic seat project was to design dynamic seating for children with extensor spasms that would be comfortable to use: seating that they could comfortably sit in without needing to be held by a parent or carer. The design began with a background of seat designs for individual children under referrals from Great Ormond Street Occupational Therapy. The final referral is described in Chapter 6. The outcome of this was a dynamic seat with linked backrest and footrest, and a saddle seat configuration. The saddle placed the child in a position with abducted hips, and allowed his whole body to extend when a spasm occurred. The backrest and footrest were linked together with a simple mechanism that moved them in synchrony. Because the child's legs were abducted, the rotation axis for the knee joints were not coaxial. The hinges for the knee joints were designed to be approximately coaxial with the child's knee joints.

The seat designed and built under the referral proved to be suitable for the child and was used daily at the child's home. However, the seat had been designed for an individual with particular need and several features that could potentially have confounded research into the effects of compliance in a seat. For this reason the new prototype generic seat was designed more conventionally without a saddle seat. It employed the same mechanism, but with more adjustment available on the spring-rate and preload, and with damping added. A list of the seat's features is given in Table 7.1.

7.2 The Seat

This section describes the first prototype seat, and the mechanical and electronic technology built into it. The section begins with a description of the support scheme that was employed for the occupant. Though the seat looked unconventional, apart from its dynamic backrest and foot support, it employed

Table 7.1: A table of the main features of the linked seat. This seat was based upon the design of the previous referral seat. See Chapter 6.

Category	Feature	Description
Support	Backrest	The full length backrest was padded with Evozote and slightly dished in profile. A four point harness and lateral supports were provided for security.
	Seatbase	The seat base was a flat level platform fitted with Evozote foam padding.
	Foot support	The foot support provided a stable platform for the child's feet . A pair of diagonal straps secured each foot to the footrest and maintained their alignment parallel to the sagittal plane.
	Head support	A Stealth i2i head support was purchased and fitted to the seat.
Mechanism	Backrest	The backrest pivoted about an axis approximately through the child's hip joint. It was connected to the foot support with a variable length link beneath the seat platform.
	Foot support	The foot support was pivoted approximately through the child's knee joint. It was connected to the backrest with a variable length link beneath the seat platform. The link enabled adjustment of the relative angles of the foot support and backrest.
Dynamics	Springs	Up to four tension coil springs could be fitted between static toggle clamps and the rear of the backrest. The toggle clamps provided for adjustment of the preload and easy unloading to enable the springs to be substituted or removed in order to vary the spring rate.
	Damping	An adjustable rate one-way hydraulic damper was fitted parallel with the springs. This enabled the seat movement to be damped on its return after a spasm.
Instrumentation	Backrest force/torque	The backrest was fitted with a pair of load cells at its top and bottom. They measured the applied orthogonal force and enabled the vertical centre of pressure to be determined.
	Backrest angle	The backrest was also fitted with a non-contact blade sensor to measure its angular position.
	Foot support torque	The foot support was fitted with a single load cell (there was not room for two) that measured the applied torque.
	Foot support angle	The foot support was also fitted with an independent angle sensor. This was because the adjustable link modified the seat geometry such that the foot support angle was not entirely linear with the backrest angle.

a conventional seating strategy and used standard off-the-shelf components where possible. A diagram of the seat is shown in Figure 7-1.

7.2.1 Support scheme

It was decided to use a conventional support scheme for this seat, positioning the occupant with hips and knees at ninety degrees when at rest. This is a commonly used seating position for children and adults alike, and is based on research by the therapy team at the Chailey Heritage school in West Sussex, England. The school has published a book[54] describing its approach to seating. See Figure 7-2 for a diagram of the support scheme used for this seat.

The seat base was initially placed parallel to the floor and adjusted to a slightly reclined position, tilted backwards at about three degrees. The seat base was fitted with castors, but was not moved whilst in use.

The backrest was positioned at ninety degrees to the seat base, and was hinged on an axis that approximately passed through the occupant's hip joint. It was made from a flat board with an Evozote foam cushion providing some pressure relief and was contoured to provide a little lateral positioning. The backrest was able to rotate backwards by about sixty degrees, with its movement being resisted by four adjustable tension springs in a frame behind the seat.

Attached to the backrest were two lateral thoracic supports that were adjustable in position vertically and, to a lesser degree, horizontally. The lateral supports were purchased from a rehab engineering supplies company and were used unmodified. A head support was also attached to the rear of the backrest. This was also an off-the-shelf item that was obtained from the a local paediatrics department. It provided occipital support, a little lateral support to the head, and could be adjusted in five degrees of freedom.

The footrest was parallel to and below the seat base when the seat was at rest. It was hinged about an axis that approximately coincided with the occupant's knee joints. The occupants knees were not abducted. The footrest could be adjusted up and down, towards and away from the knee joints.

The whole seat was mounted on a standard Jenx Gamma mobile indoor seat base with variable height and a tilt-in-space capability.

7.2.2 Structure and mechanisms

This first generic dynamic seat prototype, known as the linked seat because of the link between the backrest and footrest, was predominately constructed from mild steel, with some aluminium components. A drawing of the structure is shown in Figure 7-3.

Chassis

Two horizontal parallel steel box sections formed the main chassis of the seat slightly below seat base level. The brackets supporting hinges for the back rest were attached to these, as were the hinges for the footrest. The horizontal position of the backrest and footrest hinges could be adjusted, allowing the seat

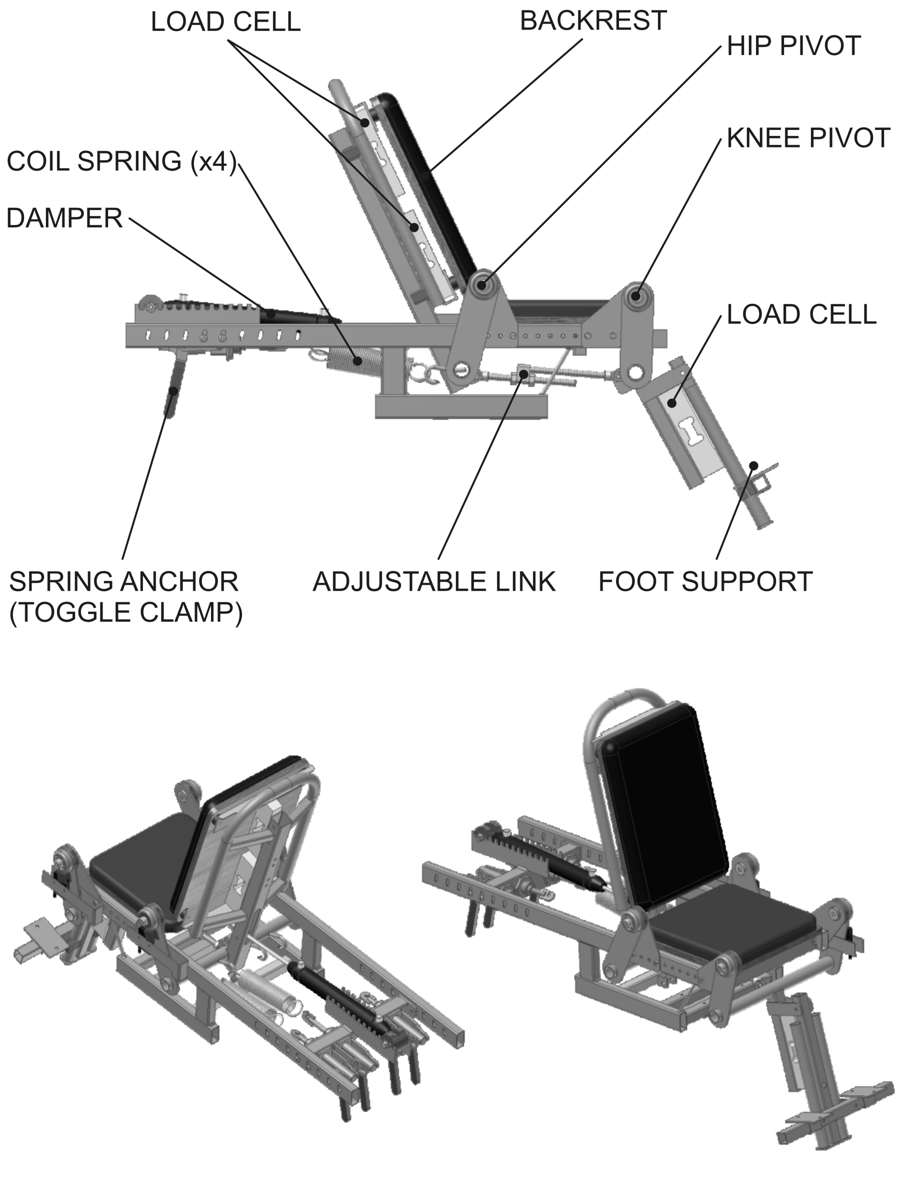

Figure 7-1: Drawings of the linked seat mechanism, showing the foot support and backrest, and the linkage between them. The springs mechanism was adjustable for preload and spring rate, and the link between the backrest and foot support was adjustable so that the relative position of the backrest and foot support could be altered independently. Overall spring rate was adjusted by adding springs or changing them for differently rated springs. Preload was modified by adjusting the position of the end of the toggle clamps that anchored the springs.

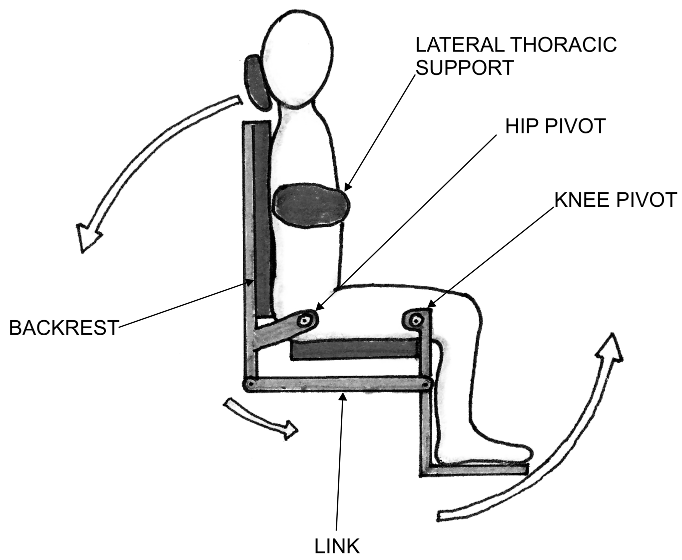

Figure 7-2: A drawing of the support and motion provided by the linked seat.

to accommodate varying femoral lengths. The horizontal box sections extended behind the backrest and also supported a bar that anchored up to four main backrest springs.

Spring mechanism

The backrest springs were steel helical tension springs that were anchored to the seat chassis with over-centre adjustable position toggle clamps that enabled the spring tension to be preset, but released without losing the tension setting when a spring needed to be changed. The geometry of the backrest springs was such that their motion, as the backrest moved during a spasm, was anticipated to be approximately equidistant either side of a vertical radial plane through the backrest rotational axis. This reduced nonlinearity in the spring characteristic throughout the range of backrest motion.

Two spring parameters were adjustable: spring rate and spring preload. The spring rate was adjusted by selecting which springs should be used, and how many to use. Two sets of four springs were acquired, one set with double the spring rate of the other. Thus the available spring rates and the minimum preloads can be seen in Table 7.2 and Figure 7-4.

Spring Extension Calculation This arrangement provided an evenly covered range of spring rates between S1rate(0.25 N/mm) and 4 x S2rate(2 N/mm). Spring preload was adjusted by modifying the position of the chassis spring anchor points using long screws in the anchor toggle clamps; lengthening or shortening the spring in the 'at rest' position with the backrest vertical.

Backrest

The backrest was hinged on a pair of ball bearings attached to brackets on either side of the steel chassis rails. Ball bearings were used to minimise any friction in the mechanism, particularly as it was being

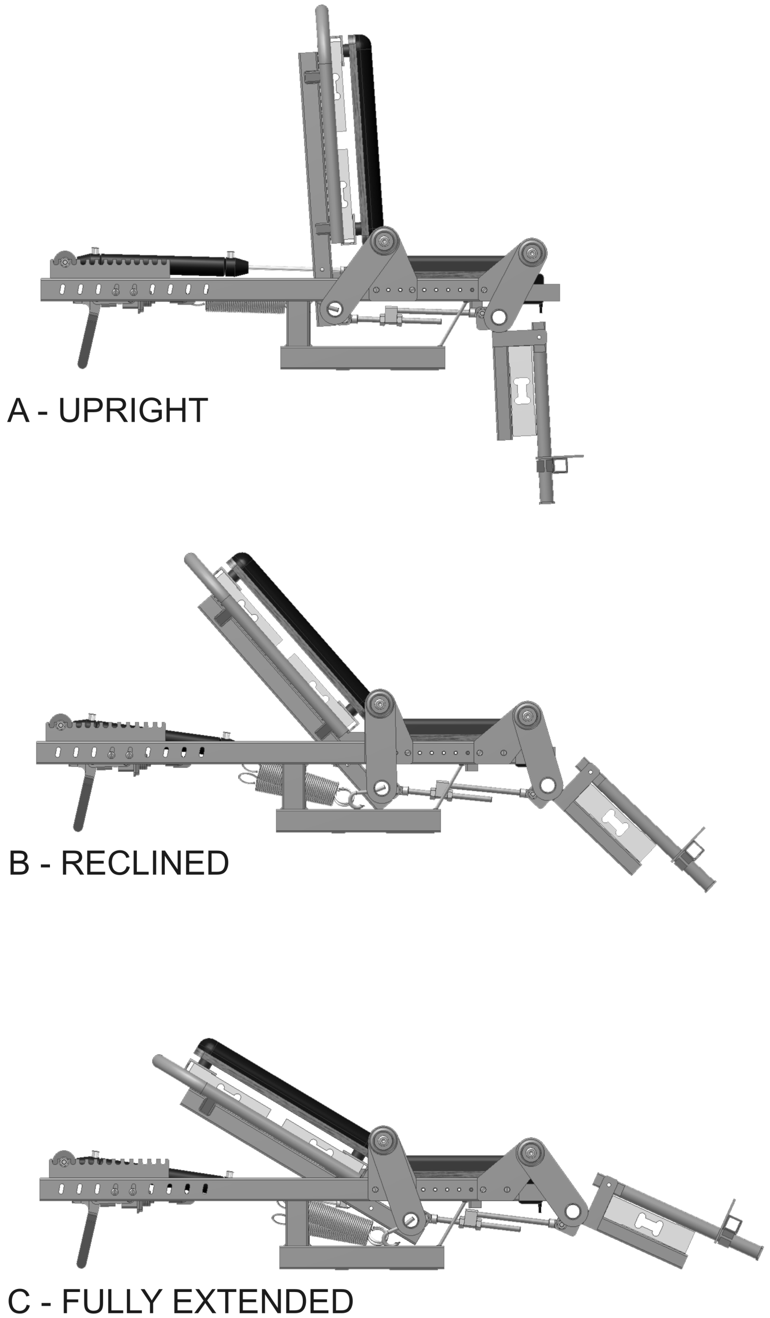

Figure 7-3: A series of three drawings showing the movement of which the seat was capable.

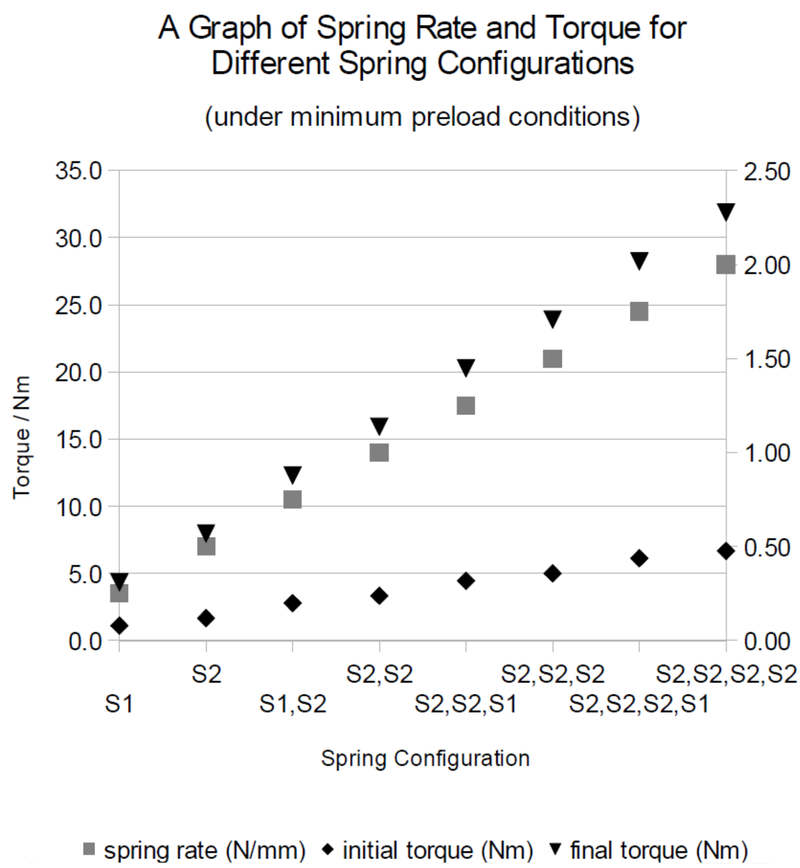

Figure 7-4: A graph showing the initial and final spring rates achievable with the selected springs, under minimum preload. It was not known at this time what spring rate would be most suitable for the children, hence the large range of adjustment in spring-rate.

Configuration	Spring Rate (N/mm)	Initial Torque (Nm)	Torque at 20° Deflection (Nm)
S1	0.25	1.6	4.3
S2	0.5	1.7	8.0
S2 S1	0.75	2.8	12.3
S2 S2	1	3.3	15.9
S2 S2 S1	1.25	4.5	20.3
S2 S2 S2	1.5	5.0	23.9
S2 S2 S2 S1	1.75	6.1	28.2
S2 S2 S2 S2	2	6.7	31.9

Table 7.2: A table of the available spring rates for spring types S1 and S2, and their impact on torque applied by the seat backrest and foot supports at 20° deflection from vertical

used for measurement. The bearings also reduced variation in stiffness from slight misalignments of the structure. The backrest frame linked the hinge points on either side of the chassis to a substantial box section member that provided a spine for the backrest board. The two backrest load-cells were mounted on the top and bottom of this spine, and the backrest board was mounted on the load-cells. The mountings for the backrest board onto the load-cells were hinged and one was provided with a short slide to prevent unwanted moments or shear forces being transferred into the load-cells. The backrest board was padded with Evozote closed cell foam and was contoured to provide a little lateral support. Additional lateral support was provided by two bought supports from the Stealth company.

Head support

The spine of the backrest was also used to mount the head support. A standard Whitmeyer support[11] was used, with two independently positionable 'wings' that provided suboccipital and some lateral support. The occipital pad was not used as it stimulated spasms. See Figure 7-6. A problem with this design was that a significant proportion of the force applied by the child during a spasm went through the uninstrumented head support and not the instrumented backrest, resulting in an unknown quantity of spasm force being unmeasured. This design error was corrected in the first and second independent seats.

Footrest

The footrest was hinged on brackets attached to the front of the chassis rails. A single central tube extended from the hinges on which was mounted a load cell. A bar on the top of the loadcell was hinged on the central tube so that the loadcell would measure applied torque rather than force. The footrest was mounted on the front of the top bar. Two foot support pads were mounted on a horizontal bar across the top bar. The foot support pads incorporated a heel cup and were fitted with straps that fastened diagonally across the pads from front to back.

7.2.3 Instrumentation

One of the main aims of this research was to develop a deeper understanding of the nature of extensor spasms, and to quantify their presentation. The design project also needed quantitative data on the

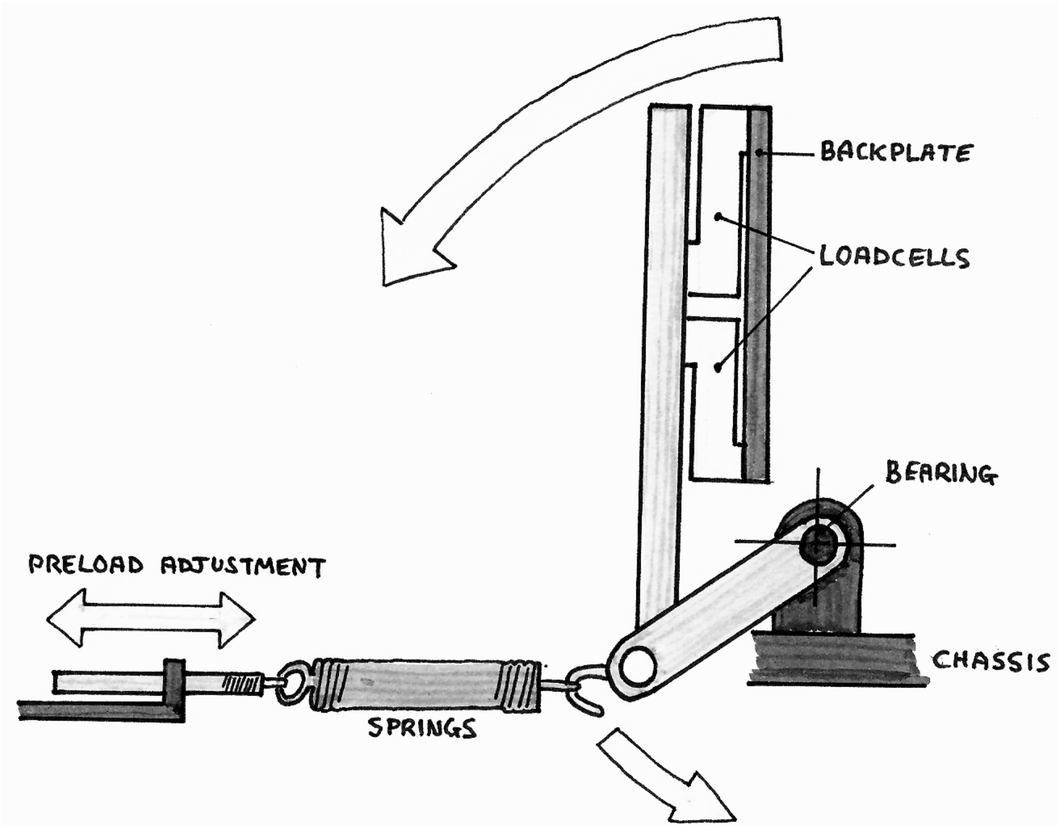

Figure 7-5: A diagram of the backrest mechanism, showing the spring positions and the approximately hip-joint aligned pivot.

torque that the spasms applied to the backrest and leg supports in order to determine the range of spring characteristics required. For these reasons the seat was instrumented using three load-cells and two angle sensors. The load-cells measured the torque applied to the footrest and the torque and position of the applied load on the backrest. The angle sensors measured the position of the backrest and the footrest. See Figure 7-8 for a diagram of the instrumentation scheme.

The specification of the instrumentation was determined by the measurement requirement. Extensor spasms are caused by muscle contractions, which are routinely measured using electromyography which uses electrodes to detect the electrical activity of the muscle during and just prior to contraction.

Torque Measurement: Load-Cells

The previous data from Brown et al[1] gave a range of possible backrest torques. A graph of this data is shown in Figure 2-1. Brown's data was used to select load-cells with a force measurement range of 0-75kg, based upon the age of the children recruited to the project and allowing a safe margin. The cells used are designed for weighing applications, and are highly tolerant of eccentric loads, maintaining their accuracy for loads applied up to 200mm away from the centre point of the nominal load platform. This feature was important on the backrest where the backrest board was mounted directly on the load-cells and would not always be loaded on its centreline.

The backrest load-cells were positioned at the top and the base of the backrest. This positioning allowed the measurement and calculation of three parameters:

1. The *total tangential force* applied to the backrest. This was the sum of the loads applied to the two load-cells. It was measured tangentially to the rotation axis of the backrest.

2. The vertical *position of the centre of action* of the force applied. This was calculated from the ratio of the top and bottom force measurements compared with the total force measurement. Horizontal variation in the position of the centre of action was not measured and did not affect the vertical measurement.

3. The *torque* applied to the backrest. This was calculated from the sum of the torques applied to the backrest through each load-cell.

Angular Position Measurement

Measurement of the position of the load cells was achieved with a pair of electromagnetic position sensors on the hip and knee joints Gill Technology blade sensors. These non-contact sensors measure changes in an electromagnetic field caused by the position of a steel plate close to the sensor. They are robust, waterproof (dribble proof) and tolerant of small misalignments. The sensors were positioned on the rotational axes for the backrest and footrest.

7.2.4 Construction and Risk Assessment

This seat, as well as all subsequent seats, were manufactured by an experienced technician in the BIME workshop. Some parts were laser profiled by an external company. The seats were risk assessed by the author, and the risk assessments confirmed by the BIME principle engineer.

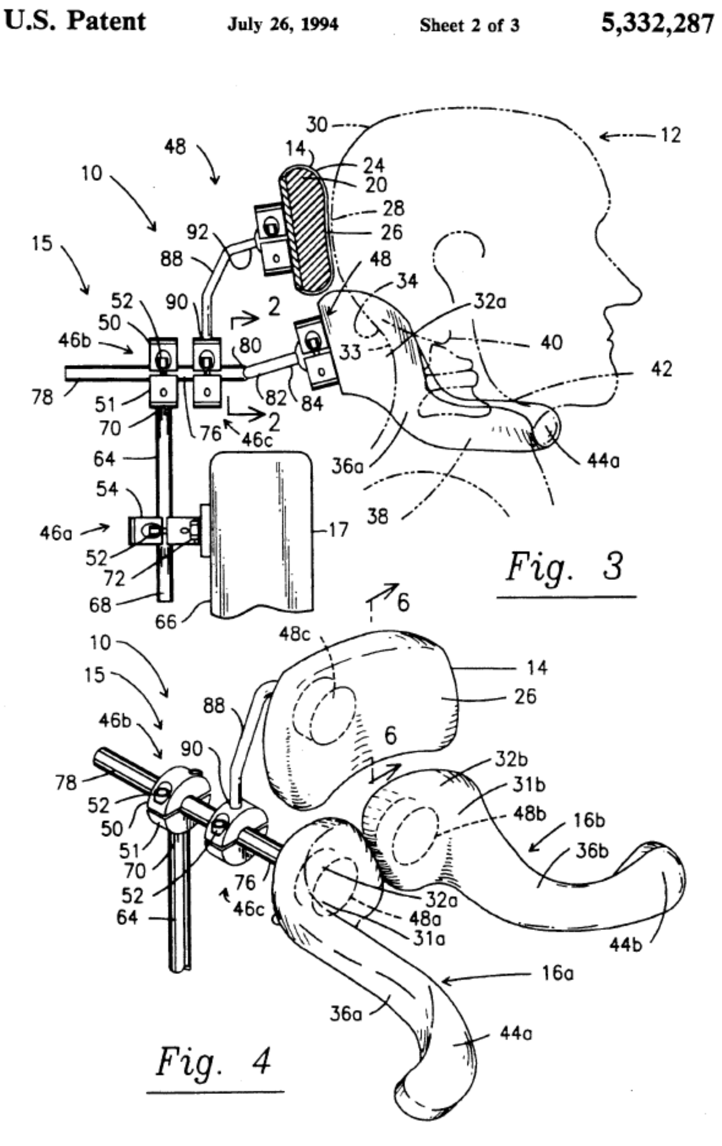

Figure 7-6: A drawing from the patent for the Whitmeyer head support[11] as used on the linked seat, showing the two independently positionable suboccipital supports (31a and 31b, Fig. 4). The occipital pad (26, Fig. 4) was not used as even mild pressure on this part of the child's head stimulated spasms.

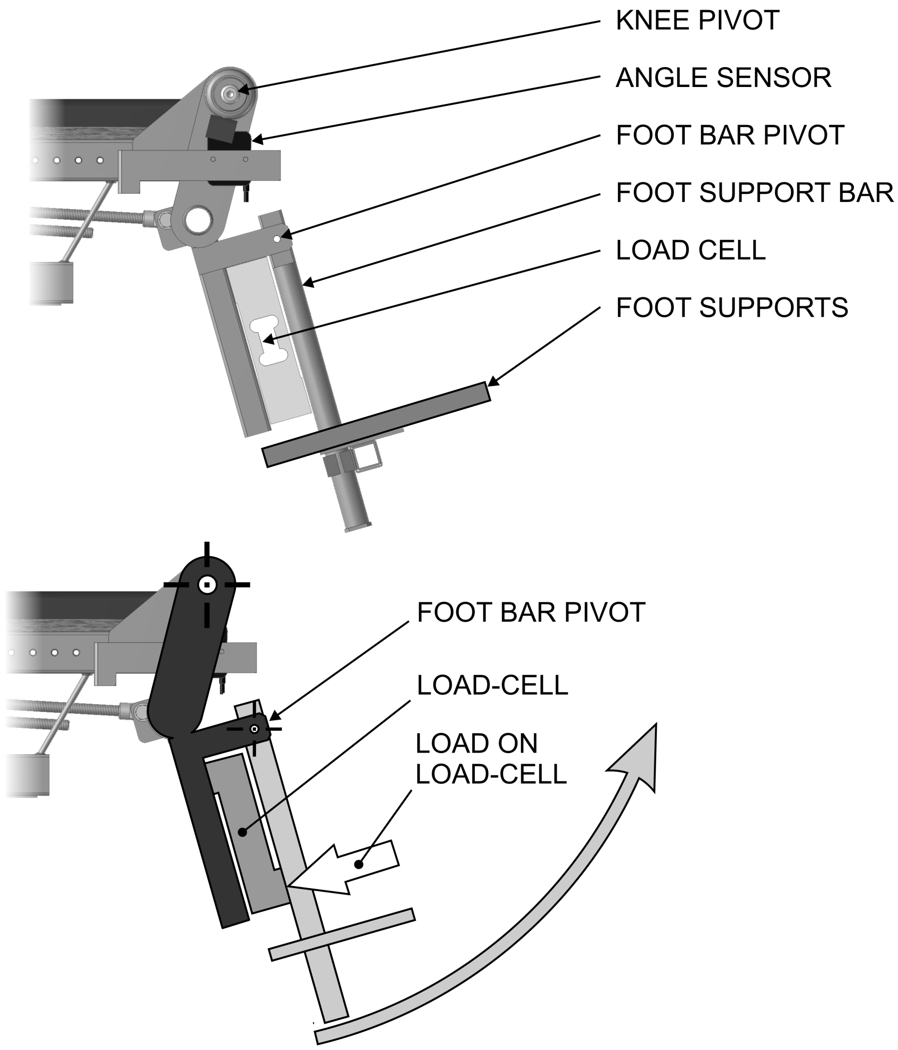

Figure 7-7: A diagram of the foot supports on the linked seat. The load cell measures the torque applied to the foot supports about the knee joint. The height of the foot support is adjustable.

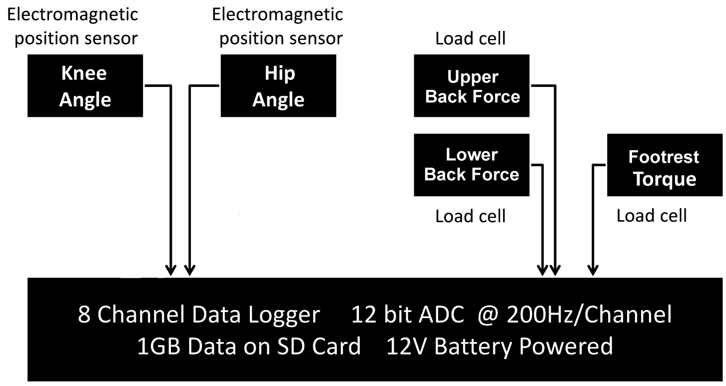

Figure 7-8: A diagram of the instrumentation scheme, showing the three load-cells and two angle sensors.

Figure 7-9: Construction of the final fully independent seat in the workshop at BIME.

Chapter 8

Linked Seat Evaluation

This evaluation was of the first seat prototype. As described in Chapter 7, it was a single degree of freedom seat with a moveable and linked backrest and footrest, hinged through the hip and knee joints. It sat the child in a conventional position with only slight abduction.

The evaluation was carefully planned, with a schedule for measurements being carefully designed for a week at the school. The effect of the seat on the child was be assessed in a series of evaluations where parameters were varied to determine an optimum configuration for the seat. The evaluation schedule incorporated:

Sixteen sessions of ten minutes each, assessing the effect of four parameters: spring preload, spring rate, motion damping and motion locking. Each session was designed to assess the effect of varying a parameter either side of the configuration established on day one.

Day 1. Familiarisation and baseline: The seat was to be tested and initially set up to suit the child using best judgement by the project team. This would establish a workable configuration that could be used as a baseline for subsequent measurements. It would also gently introduce the new seat, removing much of the child's anxiety about the new seat in a low pressure less structured situation with familiar staff and a parent present.

Day 2. 4 x Preload: The preload applied to the springs was to be varied while maintaining constant spring rate. The preload could be varied by applying an initial tension to the springs.

Day 3. 4 x Spring rate: The second day was for assessing the effect of varying the spring rate from the baseline established in day one. This was to be varied by changing the strength and number of springs fitted to the seat.

Day 4. 4 x Damping: Day four was assessing the effect of damping on the seat. This was achieved through the adjustment (and removal) of a oil filled viscous damper.

Day 5. 4 Locked and Review: Day five was for assessing the seat in a locked position with no movement in the morning, and then reviewing the week with the school staff and parents in the afternoon.

Implementing this plan was attempted, but was abandoned very early in the evaluation due to the emotional reaction of R1 to the new seat and the complexity of his disability. A more detailed description of the evaluation is given in Section 8.1 below.

8.1 Linked Seat Evaluation 1: Child R1, April 2009

Subject	Child R1
Date	23^{rd} - 27^{th} April 2009
Duration	5 days
Location	Special School
Team	Engineer (Research) Occupational Therapists (2 x Research) Teacher (School) Physiotherapist (School) Teaching Assistant (School)
Objective	To evaluate the first linked seat prototype and establish optimum dynamic parameters

8.1.1 Preparation

The introduction of the seat to the child was carefully planned to minimise the child's anxiety about new seating. For this reason the following measures were taken:

- **Environment:** The first evaluation was held in the school hall. This was a well lit and quiet room that R1 was familiar with visiting. It was felt that this environment would reduce his stress.
- **People:** The people present for the evaluation were carefully considered: the research team and R1's physiotherapist needed to be there, but he was also accompanied by a trusted teaching assistant and his mother, who was able to hold and reassure him.
- **Timing:** The seat was concealed in an adjacent room before it was introduced to R1. The plan for the morning was explained and then the seat was brought in while a more detailed explanation was given. This gave time for R1 to become accustomed to the look of the seat so that it wouldn't be a surprise when he was placed in it.
- **Realistic objectives:** The plan for the morning was not ambitious: there was time to talk and introduce the seat slowly and make time to answer any questions that the school staff or R1's mother may have had.

8.1.2 Evaluation sessions

Day 1, 23rd April - Morning – Seat Introduction: The evaluation session itself did not proceed as planned. The team assembled in the school hall and R1 was brought in by his teaching assistant. The team introduced themselves and the project and then the seat was brought in. The research engineer explained how the seat worked to R1 and his mother, and answered questions as fully as possible.

The seat was configured with 2 large springs (spring rate 1 N/mm) and no preload.

For the next stage the team attempted to place R1 in the seat. Although he was placed in the seat without much difficulty, he rapidly became distressed and had to be removed from the seat after only twenty seconds of sitting time. While sitting in the seat, R1 was bridging across the footrest, backrest and the front edge of the seat base, causing him to apply very large forces to the pelvic strap. No sensor data was collected for this initial test. After a break, R1 was placed in the seat again, but became distressed and was removed after only a few minutes.

Though the evaluation plan had been carefully designed, it did not address several key issues:

1. The first and most significant issue was that R1 had never sat in a seat that was comfortable, thus any new seat he was presented with, in his mind, would probably be at best uncomfortable and at worst painful. He had to sit and look at the strange new seat for twenty minutes while strangers talked about it, knowing that he would have to sit in it soon. This caused anxiety.

2. R1's mother was also becoming anxious about the seat. Rather than reassuring R1, his anxiety was causing her to become anxious, and this in turn reinforced his anxiety. This cycle ran for twenty minutes, considerably building R1's anxiety about using the seat.

Before the end of this session, R1 was reassured that no further seat evaluation would occur that day, which significantly reduced his anxiety. A visit to his home was arranged for the afternoon.

Day 1, 23rd April, Afternoon – Soft Prototyping: After an unsuccessful morning, the afternoon of day one was used to investigate the principles of the seat design using what was later termed 'soft prototyping' (See Chapter 4.

Linked Seat: The session initially explored the Linked Seat design, reproducing it in a soft prototype created by R1's mother and the research team as in Figure 8-1. He was seated across his mother's lap with the project team supporting his back, head and feet. He experienced spasms at this time, and the project team simulated the movement of the dynamic seat. Though R1 was sitting and moving with this support scheme, he was still lifting his pelvis from the 'seat base' (his mother's lap) and bridging as he had done in the BIME linked seat previously.

Next a slightly different approach was taken, placing his mother's arm across his legs to simulate a strap across his thighs. This worked better than a pelvic strap, and secured him more effectively, however this approach was not used subsequently because of concern that it may increase adduction and internal rotation of his hips.

This evaluation also tested different head support positions and configurations. It was found that the contact position on R1's head was critical. If it was too high (occipital), it stimulated spasms, yet if it was too low (cervical/sub-occipital), it did not provide adequate support and his head would ride up over it during a spasm. A compromise position and configuration was determined that provided sufficient support during his low-tone phase between spasms, but did not allow his head to extend excessively. A diagram of this support position is shown in Figure 8-2.

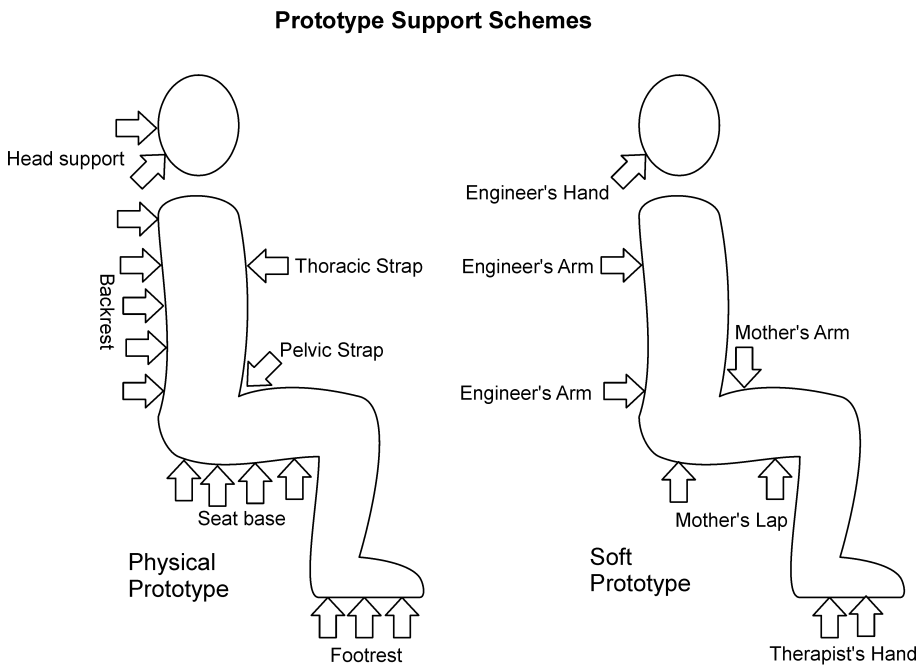

Figure 8-1: A diagram showing and comparing the support provided by the physical seat with the support provided during the soft prototype evaluation. The arrows indicate where support was provided for each prototype. The reduced support in the soft prototype was provided by the hands, arms and lap of the supporters.

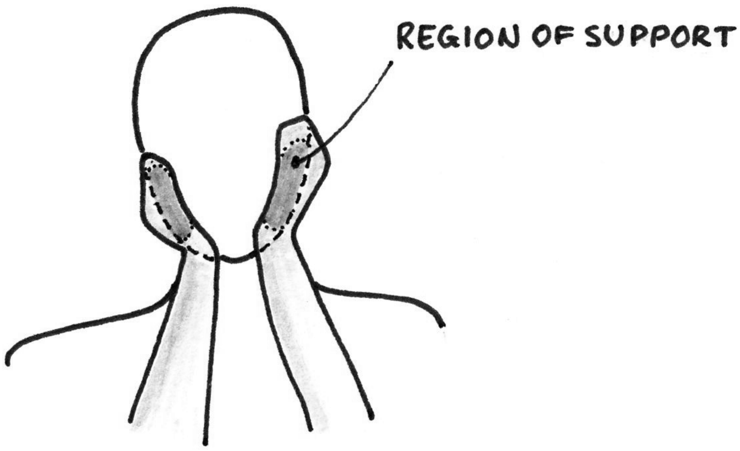

Figure 8-2: A view from the rear of R1's head showing the head support position used in the linked seat soft prototype evaluated at R1's home in April 2009. The illustration shows the posterior lateral suboccipital support position that provided sufficient head support, without stimulating spasms.

This short evaluation demonstrated that in the right environment, dynamic seating was likely to work for R1. His mother had intuitively provided dynamic seating for R1 for several years while holding him on her lap in a highly flexed position which reduced his spasms. However, while R1 was calm and had few spasms while sitting flexed (thigh/trunk angle: 40°-50°) with the reassurance of being at home on his mother's lap, in school his situation was very different. The highly flexed position was not functional and may have caused hip joint problems if used for extended periods.

At this point a brief analysis of R1's situation is valuable.

REQUIREMENT: R1 needed a seat he could use in school that was comfortable and functional for him in the classroom and at home. Without such a seat his learning would be limited and he would be held or lying down for most of the time at home.

PROBLEM 1: R1 could sit comfortably when highly flexed as he did on his mother's lap, but this was likely to cause hip dislocation and spinal problems in the future, and was not socially or physically functional. Highly flexed sitting was not an option.

PROBLEM 2: R1 could be constrained into a static seat or the BIME linked dynamic seat, but neither of these was comfortable or functional because of his powerful spasms; and discomfort made his spasms worse. Static seating was not an option.

PROBLEM 3: R1 needed a seat that was both comfortable and functional for the classroom and at home. This seat did not exist.

Independent Support: The short soft prototype evaluation that followed (see Chapter 4) was a turning point in the research that followed. R1's mother went into the kitchen with R1 to put the kettle on. The research engineer observed that when R1's mother was holding him and moving about the room, she held him in a different way to conventional seating and to how she held him on her lap. His back was held against her chest with one arm under his thighs (which were flexed up against his chest), and her other arm was around his chest. His feet were unsupported. In this position R1 was held securely, and the movement of his spasms was absorbed almost entirely in movement of his legs and rotation of his pelvis. His head was upright and he was able to see in front of him and engage socially. See Figure 8-3 for a sketch of this position.

This observation suggested a novel strategy for comfortable and functional dynamic seating: to accommodate spasms in movement only of the legs and pelvis, while stabilising the head and shoulders for function.

The strategy is summarised as follows:

1. **Stabilise the head and shoulders:** The head and shoulders should be provided with stable support to maintain hand position and eye-gaze during a spasm. Any movement of this support should be independent of any other support in the system. Spinal extension will occur during a spasm, but this must be accommodated elsewhere.

2. **Accommodate spinal extension:** If the shoulders are stabilised, spinal extension is expressed as an anterior tilt and posterior translation of the pelvis, coupled with a spinal lordosis.

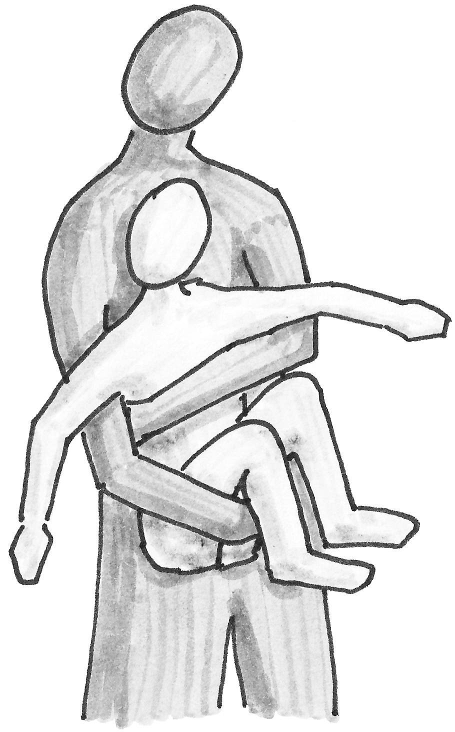

Figure 8-3: A sketch of R1 being held by his mother during the soft prototype evaluation session at his home. He is in a highly flexed position which does not support hip joint stability or spinal form, but is functional in that it allows an upright head position that facilitates social interaction and visual awareness of his environment, and substantially reduces his propensity to spasm.

3. **Accommodate hip and knee extension:** This is the largest and strongest movement of an extensor spasm. It is not necessarily symmetric, with different forces and different ranges of movement occurring in each hip. If the spine and shoulders are stabilised, hip and knee extension are expressed as a downward rotation and simultaneous straightening of the legs.

4. **Resist hip adduction:** Extensor spasms are usually associated with a simultaneous adductor spasm in the hips which laterally rotates the hips together. This movement can cause destabilisation of the hip joints and permanent deformity if allowed to persist.

5. **Accommodate foot plantar flexion:** The feet also extend, rotating downwards about the ankle joint.

R1's position when held by his mother was adapted slightly, so that R1 was seated with a hip/trunk angle of $90°$, and with some support for his head. Sustained small hip/trunk angles can result in hip dislocation in the long term and cause problems with breathing and gastric function.

This revised position was evaluated by R1's mother and the research team, and appeared to be very effective in providing a stable and functional position for R1, with minimal disturbance to his head position and field of view. It was also found during this evaluation that pressure on R1's feet increased his propensity to spasm. However, a lack of contact with his feet reduced his stability and proprioception. The position that R1's mother adopted when she held him obstructed his arm movements.

Though this position worked well for R1, implementing it in a mechanical seat was not easy. The main challenge was to determine where it would be possible for him to weight bear, particularly when he was in a near standing position. R1's mother was able to adapt her hold on him to maintain his security and stability while he moved during a spasm. In between spasms she supported him with one arm beneath his thighs that bore his weight, and her other arm across his chest, which stabilised him. She held him against herself, which provided further stability. During spasms, she allowed the arm that was supporting his thighs to move downwards, and transferred much of his weight from this arm to his trunk. She used friction between R1's trunk and her arm and chest to prevent R1 from slipping from her embrace.

It is not desirable to weight-bear in shear as was occurring between R1 and his mother's chest and arm, as shear forces are more damaging to skin than compressive forces. R1's mother provided weight-bearing through the use of compliant and actively adaptive support, which a passive mechanical system cannot do. Experimentation with possible weight bearing positions showed that the only consistently available position for weight bearing during the whole of a spasm cycle was his pelvic ischial tuberosities (upon which a cyclist weight-bears).

A novel child centred dynamic support scheme was devised, supporting social and physical function by balancing stability with freedom of movement while resisting gravity and maintaining musculoskeletal integrity:

1. **Stability for Social function:** The new seat will stabilise the head so that an upright head position can be maintained. This enables the maintenance of social eye-contact and facilitates communication using the voice and facial expression. It also means the child is more aware of his environment and that staff and peers are more aware of him.

   This will be achieved by primarily accommodating spasm movement in the legs and pelvis

2. **Stability for Physical function:** The new seat will stabilise the shoulders so that consistent shoulder position can be maintained, enabling the child to position and control his hands more easily. This means he can play and communicate with his hands more effectively, increasing his participation and engagement with social and educational activities.

   This will be achieved by primarily accommodating spasm movement in the legs and pelvis

3. **Freedom of movement:** The new seat will allow extensive independent freedom of movement of the each hip and knee and some movement of the spine. Specifically, it will allow spasm movement to take its course, and then restore the occupant to a stable and functional position after a spasm. Maintaining low resistance to movement means that:

   (a) Spasm induced movement will be less disruptive to functional head and hand position.

   (b) The occupant can use volitional seat movement to adapt posture to function, improving the child's ability to engage, communicate and respond to communication using posture and movement.

This will be achieved by providing independent dynamic leg supports and a dynamic back support that allowed controlled movement.

4. **Resisting gravity:** The new seat will comfortably bear the weight of the child, supporting him at an appropriate height above the ground for a full range of activities. The seat will support a low tone child in maintaining functional anti-gravity postures, yet also allow the child to develop their strength and their own anti-gravity strategies.

5. **Supporting homeostasis:** The new seat will support the maintenance of the proper functioning of the skeleton, muscles, skin and other organs. This means that it will:

   (a) Support correct musculoskeletal alignment and inhibit deformity;

   (b) Maintain skin integrity by reducing contact pressures;

   (c) Support other functions such as digestion and breathing though appropriate positioning.

Days 2-5, 24th April - 27th April: Following the dramatically unsuccessful first evaluation session, and the devising of a new support design during the soft prototyping session, the next three days were spent at R1's school, working with him in the linked seat and attempting to adjust and modify it so that R1 was able to sit in it for periods longer that the initially achieved twenty seconds. The author did not want to immediately abandon the existing seat, which was based on successful previous work, for a novel support scheme that was only partially implemented and evaluated. Nevertheless, the novel scheme was derived from a first-principles analysis of the support needs of the child, and offered a child-centric approach to seating for children with whole body extensor spasms.

Several changes were made to the linked seat over the course of the week:

1. The foot plate was removed, so that R1's feet were unsupported, but support for his calves was retained. It was not possible to quickly modify the foot support to provide partial support due to its design.

2. The head support was changed from a conventional occipital support (based on a the posterior component of a compliant neck collar) to a Whitmeyer suboccipital support in accordance with the head support findings obtained during the soft prototype evaluation.

3. The anchor points of the pelvic strap were moved posteriorly to reduce constraint of vertical movement of the pelvis while increasing resistance to anterior tilt of the pelvis and increasing resistance to forward movement away from the seat back.

4. The hydraulic damper was removed. This reduced the resistance of the seat to R1's spasms, and seemed to reduce the forces he applied to the seat.

8.2 Summary of the Evaluation Findings

1. Dynamic seating is likely to be able to provide comfortable and functional seating for children with whole body extensor spasms

2. It is likely that increased stabilisation of the head and upper trunk is possible through a support scheme that prioritises motion of the legs over motion of the back and pelvis.

3. Likely sites for weight bearing are: ischial tuberosities (main), thighs (major partial), feet (minor partial).

4. Pressure applied to the sole of the foot either through weight bearing or dynamic movement should be moderated so as not to stimulate spasms.

5. Pressure applied to the back of the head through a head support can increase spasm stimulus. This should be taken into consideration when specifying or designing a head support.

6. Movement of the foot and back supports should be independent to prevent the occupant 'bridging' across them, weight bearing on the back of his shoulders and his feet.

7. Damping was not found to be helpful and was removed. R1's spasms were less intense when the resistance of the hydraulic damper was removed.

8. The environment in which the evaluations were conducted were critical to their success or failure. R1's emotional state had a very significant effect on his spasm frequency and intensity, and a calm, familiar and distracting environment reduced or eliminated his distress.

9. The people present during the evaluation also significantly affected the success of the evaluation. People who were calm, trusted, and consistent (teacher, favourite teaching assistant) improved his emotional state. People who were anxious or not trusted (mother, physiotherapist, research team) adversely affected his emotional state. It should be noted that, of the school staff, R1's teacher was most demanding in her expectations and management of his behaviour, but was also the most skilled and patient in understanding his non-verbal communication.

Part IV

Whole Body Dynamic Seating

Chapter 9

Independent Seat - Feasibility Study

A seat allowing independent movement of the lower limbs and back

This chapter describes a feasibility study into the design of a seat based upon the support scheme devised in Section 8.1.2 which allowed independent movement of the lower limbs and back. It sets out the process of defining the specification for the design of the first independent seat. Soft and semi-soft prototype evaluations were used with both children (A1 and R1), which progressively reduced the uncertainty around the proposed design. This chapter also describes the implementation of the soft and semi-soft prototyping methods described in Chapter 4.

The feasibility study was designed to progressively explore the feasibility of the independent seat concept, and reduce the risks and unknowns surrounding its implementation. The study investigated and defined the user interface requirements, and determined a specification for the final fully functional seat. It began with an investigation into foot and hip positioning with Child A1.

9.1 Independent Seat Soft Prototype Evaluation 1: Child A1, May 2009

Subject	Child A1
Date	7^{th} May 2009
Duration	1 day
Location	Special School, London
Team	Engineer (Research) Occupational Therapists (2 x Research, 1 x School) Teacher (School) Teaching Assistant (School)
Objective	To evaluate and develop the independent support scheme.

9.1.1 Evaluation Objectives

This qualitative evaluation was conducted after the first evaluation of the linked seat. Its aim was to assess the new approach that was based upon the observation of the intuitive holding by R1's mother; and ascertain if it was likely to be successful for child A1. Because of the fundamental 'bridging' issue identified during the evaluation of the linked seat by R1, it was decided to explore alternative seating strategies with A1. In retrospect it may have been better to have evaluated the linked seat with A1 at this stage, however time for the project as a whole was short and it was decided to take a risk and start work on the new support scheme inspired by R1's mother, as it was considered that this was more likely to be successful in the long term.

9.1.2 Evaluation sessions

A1 was assessed at his school in the physiotherapy gym. He is a less anxious child than R1, and seemed to enjoy working with the research team and his therapists.

The main investigation carried out in this session was to explore the support and positioning of A1's feet and legs, and in particular to determine a) if his hips should be abducted; and b) how his feet should be supported and whether they would be able to weight-bear.

A1 was sat astride a therapy roll (a large cylindrical bolster cushion that is used for positioning children during physiotherapy). He was held securely from behind by one of the research therapists, while his own therapist and the other research therapist and engineer knelt either side of him and supported his feet and legs. In this position, the effect of varying his hip abduction angle and the degree of support provided to his feet could be easily observed. He was seated in this position to approximately simulate the support provided by the proposed independent seat.

It was found that hip abduction angle did affect his spasms. Applying some abduction (about 15° from the midline per leg) appeared to reduce his spasm intensity and his sensitivity to spasm triggering. If too much abduction was applied, he became discomforted. The abduction was applied through a hand positioned on his inner thigh slightly distal to his knee.

The degree of constraint applied to his feet was also found to affect spasm triggering. Although constraining his feet rigidly meant he could weight-bear through his feet, his sensitivity to spasm triggering increased. If his feet were unconstrained, his sitting stability and security worsened, again resulting in increased spasm trigger sensitivity. If no support was provided through his feet, then he was not able to weight-bear through them at all. The most successful support design found at this time was to partially constrain his feet. His feet were maintained parallel to the therapy roll, and slight pressure was applied to his soles. See Figure 9-1

This evaluation also explored how back support should be provided. It was found that some backrest movement was needed to accommodate his spasms (about 20°) but not so much as was provided by the linked seat (about 70°). It was also found that this child needed secure support laterally and anteriorly to maintain good posture, and particularly an upright head position, as when not experiencing a spasm his low background tone resulted in his head falling forwards and his shoulders moving forwards and towards the midline.

Figure 9-1: A1 evaluating a soft prototype of the independent dynamic seat, using a therapy roll as a prop.

Although initially A1's pelvis was unsupported, it was difficult to maintain axial rotational alignment. Subsequently A1's pelvis was supported by a therapist sat behind him who applied her hands to his left and right Anterior Superior Iliac Spines (ASIS) and posteriorly to the Iliac Crests, holding them firmly to maintain alignment.

9.1.3 Conclusions

Several conclusions were drawn from this evaluation:

1. The child should be seated with his hips slightly abducted (Approximately 10° from midline) to reduce spasm trigger sensitivity and intensity.

2. The child's feet should be aligned to the midline of the seat, with partial weight-bearing though the soles. Plantar flexion of the foot should be allowed during a spasm.

3. Some backrest movement was likely to be necessary (about 20°), but much reduced when compared with the earlier linked seat (about 70°).

4. The child is likely to need secure support to the upper trunk.

A month after the end of this evaluation, the research team met to discuss the results and decided to take a considered risk and pursue the independent seating approach initially explored with R1's mother, in preference to the more conventional Linked Seat approach used in the first evaluation and in previous work. There were not sufficient project resources available to pursue both concepts simultaneously.

The new approach prioritised function, attempting to stabilise the head and shoulders of the child, while allowing the pelvis, hips and knees to move during a spasm. It was expected that the new approach would result in substantially less disruption to the position of the functional head and shoulders during a spasm. It was thought that the new approach would require the use of a saddle seat to enable the child to weight-bear during a spasm. An equestrian saddle was purchased for initial exploration of this approach.

9.2 Independent Seat Soft Prototype Evaluation 2 (Equestrian Saddle): Child A1, 23rd June 2009

Subject	Child A1
Date	23rd June 2009
Duration	1 day
Location	Special School, London
Team	Engineer (Research) Occupational Therapists (2 x Research, 1 x School) Teacher (School) Teaching Assistant (School)
Objective	To assess the suitability of an equestrian saddle for providing a seated position.

9.2.1 Evaluation Objectives

This evaluation was of an child's equestrian saddle with additional trunk and foot support provided by the research team. Reflection on the previous evaluation had suggested that the pelvic and upper leg positioning required could be achieved with an off-the-shelf child's equestrian saddle. which provided a ready made model for a saddle seat that could be quickly obtained and assessed.

9.2.2 Evaluation session

A saddle was obtained and evaluated at A1's school in the physiotherapy gym as in previous sessions. A1 was initially seated on a therapy roll and the previous findings were confirmed. Figure 9-2 is a view from above, showing head and truncal support being provided by a therapist. His hip asymmetry can also be seen.

The saddle was placed over the therapy roll and A1 was seated on the saddle. His back was partially supported by the school physiotherapist, and his feet by the research therapist and (at times) the research engineer. A1 was not distressed at this time, and experienced some spasms. The team simulated the action of a dynamic seat modelled on the principles developed at R1's home. His feet were supported and allowed to move independently with little resistance, though their alignment was maintained. His pelvis was stabilised by the saddle, and also by the school physiotherapist who was sat astride the therapy roll close behind him, using her body to stabilise him. Her arm around him maintained his

Figure 9-2: A view from above A1 while he is being seated on a therapy roll. This view shows his head and thoracic support, as well as his hip asymmetry

trunk position. A1's head was supported on the school therapist's chest and stabilised with her hand. A1 was not so sensitive to occipital support as R1. See Figure 9-3.

In addition to evaluating the saddle as a prototype of a seat, several foot support options were evaluated, including:

1. Placing a hand beneath his foot and holding his ankle, while maintaining sole contact during spasm.
2. Placing a hand beneath his foot and holding his ankle, while allowing his heel to lift from the sole contact during a spasm;
3. Placing a hand beneath his foot and another across his toes while maintaining sole contact during a spasm;
4. And lastly, placing a hand beneath his foot and another across his toes.

9.2.3 Conclusions

1. The equestrian saddle provided good pelvic support for A1 in an abducted seated position. He was stable and was not distressed by his positioning. A1 was weight-bearing on the saddle, with medio-lateral contact on his inner thighs creating the abducted leg position.
2. The lateral thigh contact was effective and comfortable in its positioning of A1, however it also created friction between A1's inner thigh and the saddle. Because of A1's powerful hip adductor spasm which occurred simultaneously with his extensor spasm, the friction between his inner thigh and the saddle was sufficient to impede the movement of his legs, and cause increased spasm intensity and asymmetric displacement of his pelvis.
3. Independent foot support was needed to accommodate asymmetry in A1's spasms, and further reduce asymmetric displacement of his pelvis on the saddle.

This evaluation showed that a seated position with abducted hips, independent foot support, a large range of movement for hip extension and a small range of movement for spinal extension was likely to be successful for A1 and possibly other children with a similar disability.

At the time of this evaluation, recruitment of further children was still in progress, but no further children had been admitted to the project at this time. Considering the time and funding left for the remainder of the project, it was decided to proceed with the design of a semi-soft seat prototype based on the independent seat concept developed using soft prototyping.

9.3 Semi-soft prototype seat design

Based upon the results of the soft prototype evaluations, the following specification was determined for the independent seat:

1. The seat should have independent hip, knee, foot and backrest movement;

Figure 9-3: A photograph of the A1 sat on the equestrian saddle between evaluation sessions.

2. A saddle seat should be used to abduct the user's hips - this could be achieved using 'gutters' to support and constrain each thigh;
3. A minimal saddle should be used to support the user's weight;
4. The sensation of pressure on the user's feet should be reduced, therefore the user should wear shoes to reduce sensation on the sole of the foot;
5. The 'at rest' hip angle should be able to be adjusted to slightly less than 90°.
6. The seat should have a tilt–in-space facility.

A semisoft seat prototype was designed to model such a seat and test the hypothesis that allowing substantial independent movement of the legs during a hip extensor spasm would stabilise the head and shoulders, and be less disruptive to the child. The semi-soft prototype (see Figure 9-4) supported the child with a backrest, a bicycle saddle, and two independently hinged thigh gutters. The backrest and thigh gutters were hinged on an axis approximately through the hip joints. Head support was provided by a suboccipital fold of closed cell foam on the extended backrest. The seat did not provide foot support. This support was provided directly by the hands of the evaluation team (See Section 4.5). There were no springs or other force application mechanisms built into the seat, thus it was dynamically unconstrained. It became known as the "Floppy Seat" as without human support it would not support an occupant. For a child to be seated in the floppy seat, the seat needed to be provided with structure by the evaluation team.

This seat was simple in its implementation, and was designed quickly to a functional, non-aesthetic design using available components where possible. It was intended that it should confirm or refute the new proposed seating strategy with minimal cost in time and other resources. The seat was not instrumented due to the design and analysis time required to implement instrumentation.

9.3.1 Base

The base of the seat was floor standing and utilised a five leg office chair base. The base consisted of five evenly spaced horizontal legs radiating from a central vertical tube. On the top of this tube, a children's bicycle saddle was fixed. The saddle fixing bracket allowed some forwards/backwards position adjustment, as well as adjustment to the saddle tilt angle.

A wide ∪ shaped mild steel component (the Hinge Bracket) was clamped to the base tube slightly behind and below the saddle such that its vertical position could be adjusted up and down the tube. The ends of the arms of this component were drilled and formed the part of the hinge for the backrest and thigh supports, which in this seat were coaxial.

With the forwards/backwards adjustment on the saddle and the vertical adjustment possible with the hinge bracket, the rotational axis of the thigh and back supports could be adjusted to approximately align with the child's hip joint rotational axis.

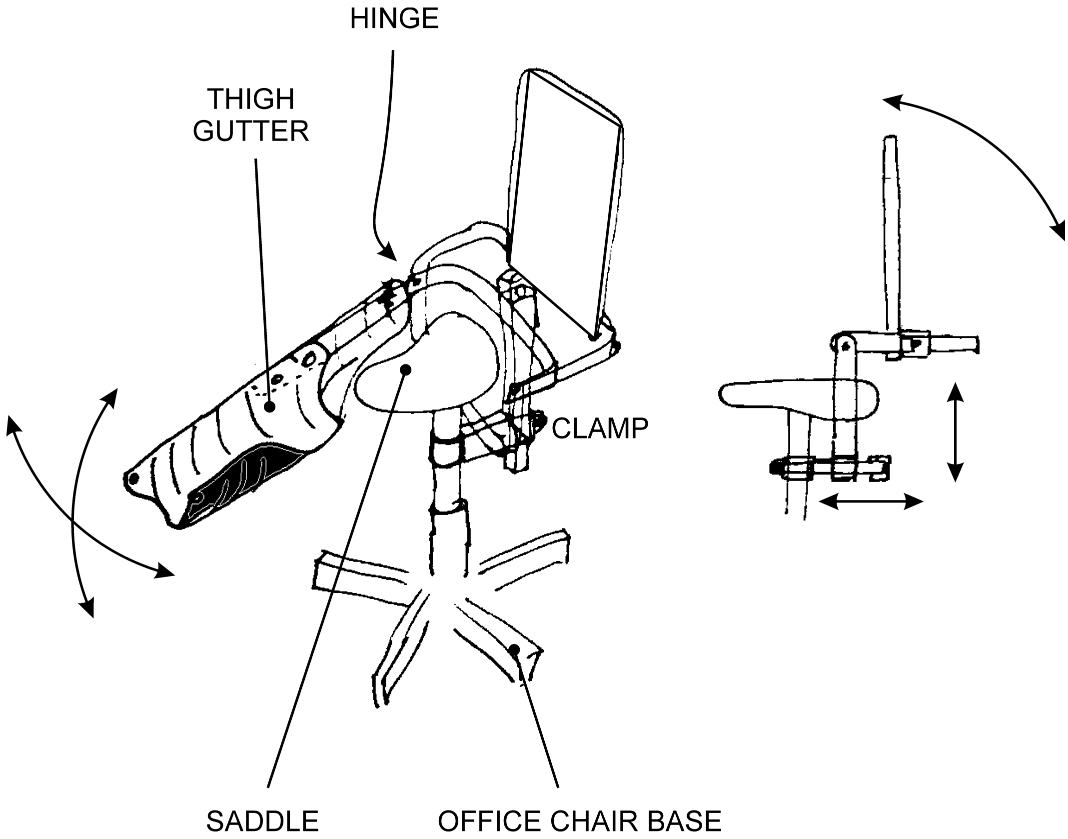

Figure 9-4: A simple design sketch of the semi-soft prototype (LEFT), showing the uncomplicated design and the base, backrest and thigh supports. The small sketch (RIGHT) shows the up/down and forwards/backwards adjustment of the backrest and thigh support position; along with the rotation of the backrest.

9.3.2 Backrest

The backrest was simply hinged on steel pins through the ends of the Hinge Bracket. No bearings were installed. It had a simple steel frame with a plywood board attached to its front, which was covered in 12mm thick Evozote closed cell foam. The foam was folded back on itself at the sides to present a dished profile to the child that would provide a little lateral support. Standard off-the-shelf lateral thoracic supports from the linked seat were fitted to the lateral bars of the backrest. There was a 50mm offset between the rotation axis and the front of the backrest board. This dimension was fixed. Adjustment of the offset of the child from the back board was possible by applying additional thicknesses of foam to the front of the backrest board.

9.3.3 Thigh supports

The two thigh supports were pivoted on opposite sides of the Hinge Bracket. Each consisted of a steel bracket extending from the pivot. The bracket itself was hinged, allowing the thigh support to rotate up and down on the Hinge Bracket (through the hip joint axis) and rotate left and right on the hinge fitted to the support between the Base hinge point and the thigh tray.

9.3.4 Operation

The ‘floppy seat’, as it became known, was operated by a team of people according to a coordinated plan. The people holding the support surfaces imbued them with approximated dynamic properties by virtue of how they responded to the movement of the child. For example, a joint fitted with a constant tension spring with low spring rate but high initial tension might be simulated by a person who resists initial movement up to a certain ‘force’ level, and then allows the joint to move with very little further resistance. See Figure 9-5.

9.4 Independent Seat Semi-Soft Prototype Evaluation 1 (Floppy Seat): Child R1, 28th September 2009

Subject	Child R1
Date	28th September 2009
Duration	1 day
Location	Special School, Essex
Team	Engineer (Research) Occupational Therapists (2 x Research) Physiotherapist (School) Teaching Assistant (School)
Objective	To evaluate the suitability of a semi-soft prototype seat modelled on the independent seat concept.

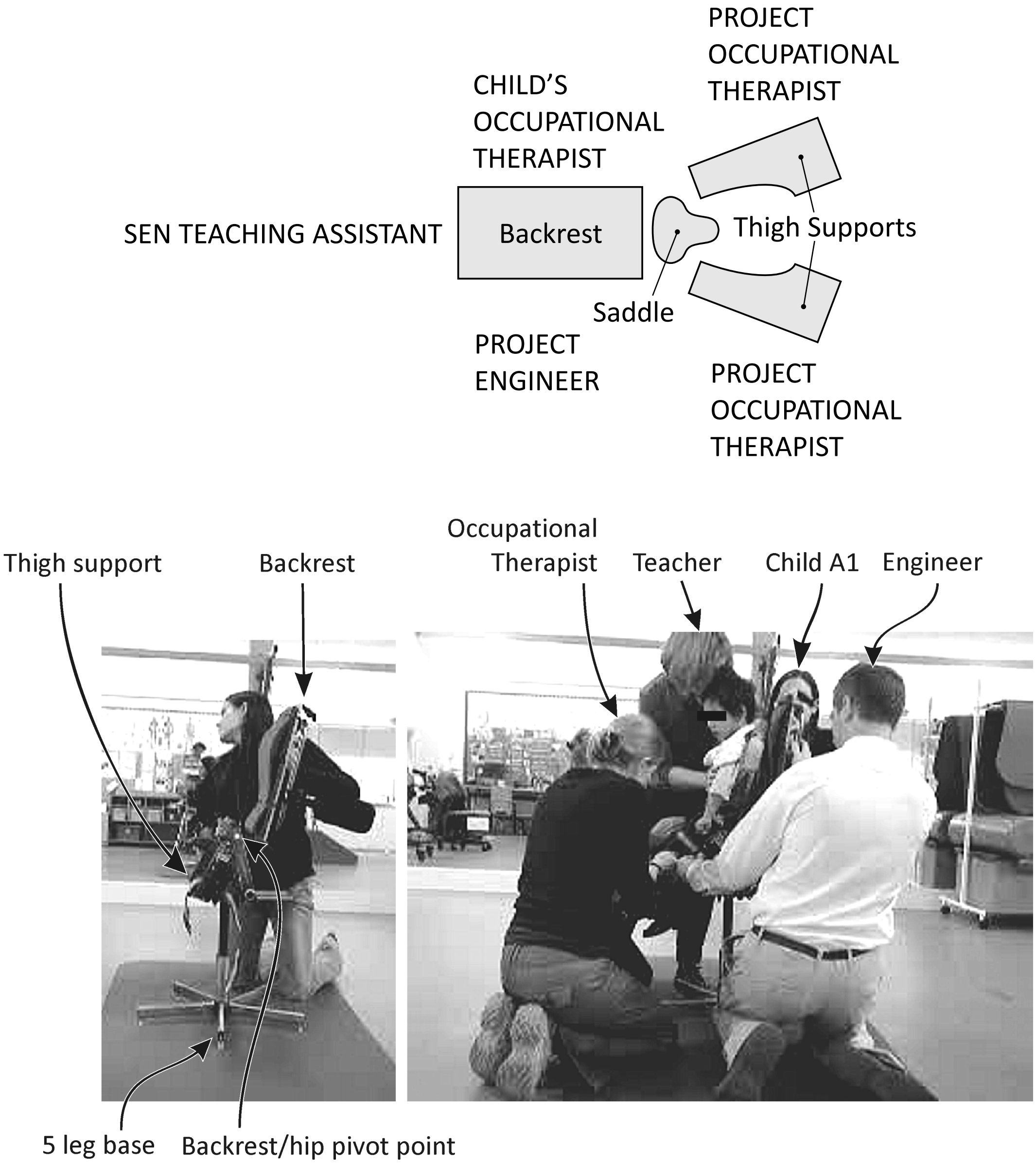

Figure 9-5: TOP: A diagram of the supporting team around the floppy seat prototype. BOTTOM: Two photographs of the team during an evaluation.

9.4.1 Evaluation objectives

The primary objective of this evaluation was to test the geometry and function of a simple kinematic implementation of the independent seat with Child R1. This prototype is described in detail in Section 9.3. See also Figure 9-5.

The evaluation was designed to assess the approach of stabilising the shoulders in providing a comfortable seat for child with whole body extensor spasms by:

1. Minimising constraint forces. This was achieved by:
   (a) Allowing spasms to be dissipated in free movement of the limbs and body;
   (b) Designing the seat pivots to be co-axial with the the evaluator's joint where possible.
   (c) Applying only constraints as are necessary for the security and function of the child.
2. Stabilising the head and shoulders. This was achieved by:
   (a) Absorbing spasms through displacement of the legs and pelvis,
   (b) While minimising movement of the head and shoulders through careful selection of relative thigh support and backrest 'spring rates'. In this evaluation, the backrest operators simulated stiffer springs than the thigh support operators.

9.4.2 Preparation

A description of the method for this evaluation is given in detail in Chapter 4. It is summarised below.

The evaluation was planned to occur in R1's school multi-sensory room. This was a relaxing environment which R1 enjoyed. The staff present were chosen carefully to be those necessary for the evaluation and also those whom he trusted. The exception to this was his physiotherapist who he did not trust. However, she needed to be present, so her assigned role was to support the backrest from a position out of sight of R1.

The team physically rehearsed the support they would be providing using the semi-soft prototype, and checked that they were coordinated. Unfortunately, R1 was brought prematurely into the therapy room where the team were rehearsing, and began to be distressed. Rather than delay the evaluation and disrupt R1 further by taking him out and back in again, the team opted to proceed with the evaluation at that time.

9.4.3 Evaluation

R1 was placed in the seat and secured in place with the thigh straps and the lateral thoracic supports. He was initially very unsure about the seat and began to become distressed. However the distress passed and he relaxed into the seat and began to enjoy sitting in it. This was a significant contrast with his reaction to the previous linked seat prototype that he had sat in. The new prototype was clearly comfortable for him. His constraint forces were substantially reduced, and he sat symmetrically, even though his spasms were frequently asymmetric. See Figures 9-6 and 9-7.

Figure 9-6: A photograph showing R1 (TOP LEFT) being brought to the seat (CENTRE) at the beginning of the evaluation.

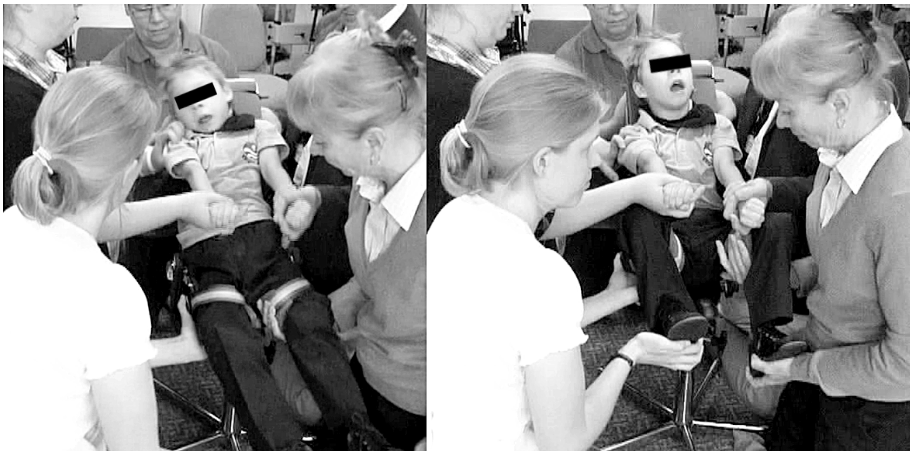

Figure 9-7: Two photographs showing R1 in extended (LEFT) and flexed (RIGHT) postures. At this time he was alternating between flexor and extensor spasms at about 1Hz (10 spasms counted over 10 seconds). The team supporting him can be seen around him. The team present are (clockwise from the bottom left): Research Occupational Therapist, Teacher, School Physiotherapist, Research Engineer, Research Occupational Therapist. The video camera was operated by R1's classroom assistant.

9.4.4 Evaluation Summary

This evaluation achieved several outcomes:

1. R1 sat comfortably in this seat without being distressed, and seemed to enjoy the movement it enabled.
2. R1's pelvic symmetry was good, with the seat allowing asymmetric movement.
3. Constraint forces on the pelvic strap were much lower than in the linked seat.

9.5 Independent Seat Semi-Soft Prototype Evaluation 2 (Floppy Seat): Child A1, December 2009

Subject	Child A1
Date	10^{th} December 2009
Duration	1 day
Location	Integrated mainstream / special school, London
Team	Engineer (research) Occupational therapists (2 x research, 1 x school) Teaching assistant (school) Teacher (school)
Objective	To evaluate the suitability of a semi-soft prototype seat modelled on the independent seat concept.

9.5.1 Evaluation objectives

The objectives of this evaluation with Child A1 were the same as the previous semi-soft prototype evaluation with Child R1: to observe the child sitting in a partial simulation of the proposed independent dynamic seat and qualitatively explore its configuration and dynamic properties.

9.5.2 Preparation

The evaluation was planned to take place in A1's physiotherapy gym. This was a quiet location with plenty of space where he would not be disturbed. The team planned and rehearsed the course of the evaluation before A1 was brought into the room. The evaluation plan was straight-forward:

1. The seat was to be set up for the evaluation with the video camera in position and running;
2. A1 was to be introduced to the research team and the plan for the evaluation explained to him;
3. A1 was to be placed in the prototype seat after a manual transfer from his usual seating;
4. He was to be secured in the prototype seat by the support team;
5. A1 was to be observed sitting in the seat;

6. And finally he was to be removed from the prototype seat and returned to his usual seating.

9.5.3 Evaluation

The evaluation proceeded as planned. After rehearsing the evaluation, A1 was brought into the room, he was introduced to the evaluation team. The engineer started to explain what was going to happen during the evaluation, and as he did so, A1 recognised his voice and grinned. Clearly his expectations of the evaluation were positive. See Figure 9-5.

With the video camera running, A1 was placed in the seat. He appeared to sit comfortably in the seat, but several issues were identified:

1. He exhibited significant spinal extension, which caused his lumbar spine to move away from the backrest.

2. A1's pelvis displaced, with an anterior tilt and an axial rotation to the left.

3. A1 was able to hyper-extend his hips (femur/trunk angle $> 180°$), which contributed to the displacement of his pelvis as the posterior surface of his thighs (especially his right thigh) levered against the front edge of the saddle during extensor spasms.

9.5.4 Conclusions

This evaluation differed from the previous evaluation with R1. A1 showed greater asymmetry and hyper extension of his hips. He also extended his spine more than R1. He also appeared to be more comfortable and was not distressed while sitting on the seat.

While the evaluation was considered successful because the primary objective of a comfortable seat had been achieved, there were significant problems to be overcome in a subsequent implementation of a fully independent dynamic seat: the seat should accommodate large asymmetric hip extensions and spinal extension.

Though these problems were identified, the seat was nevertheless comfortable to A1. This was significant progress towards the original research objective. The evaluation confirmed the principle of seating a child with whole body extensor spasms with a seat that could accommodate the spasms with little resistance while allowing asymmetric movement and absorbing spasm in the legs as much as possible.

9.6 Summary of Soft and Semi-soft Prototype Evaluations

The series of soft and semi-soft prototype evaluations showed that:

1. A dynamic seat with independent movement of the legs and backrest was likely to be able to provide seating suitable for some children with whole body extensor spasms.

2. The emotional state of a child evaluator has a significant impact on the evaluation, directly affecting the child's physical response to the seating being evaluated.

3. An independent dynamic seat that prioritises leg movement over backrest movement results in stabilisation of the child's head and shoulders when compared with a backrest only seat or a seat with linked backrest and leg movement.

The evaluations resulted in a detailed specification for the first fully functional independent seat. This specification is set out below:

Backrest specification:

1. The backrest should permit 15° to 20° of extension from the upright position.
2. The backrest should have a linear spring characteristic with a configurable preload.
3. The backrest should be designed such that lumbar contact with the backrest is maintained in an 'at rest' sitting position.

   NOTE: The backrest for the first independent seat was hinged at a point above and behind the hips to reduce the loss of contact with the lumbar spine that was observed during A1's evaluation of the semi-soft prototype. This was an experimental configuration that was later abandoned in favour of a joint centre coaxial with the occupant's hip joints due to the substantial increase in pelvic constraint forces and displacement of the spine along the backrest during movement.

Pelvic support specification:

1. The pelvis should be supported such that axial rotation is prevented, but limited tilt is allowed.
2. The pelvis should not be able to rise away from the weight-bearing saddle.
3. Pelvic constraint forces should be minimised.

Leg support specification:

Leg supports

1. The seat should provide two independently jointed and independently adjustable leg supports.
2. The leg supports should be jointed at the hips, knees and feet.

Thigh supports

1. The hip joints should be coaxial with the occupant's hip joint, and should allow 70° of hip extension from a sitting 90° femur/trunk angle.
2. The hip joints spring rate characteristic should be close to flat with preload to balance the weight of the legs. This spring rate characteristic will create minimal resistance to hip extension once the preload has been overcome.
3. The hip joints should not hit a rigid stop when in motion induced by the occupant.

4. The hip joints should resist extension of the hips that opens the at rest 90° femur/trunk angle during sitting; but it should not assist flexion of the hips, closing the at rest 90° femur/trunk angle during sitting. This will tend to maintain a 90° femur/trunk angle during sitting, but allow flexion and extension to occur during a spasm.
5. The thigh supports should abduct the hips and strongly resist adductor spasm. The angle of abduction should be adjustable.

Foot support

1. The knee joints should be hinged freely and should be coaxial with the occupant's knee joints.
2. The foot support should provide continuous contact with the sole of the occupant's feet at rest, while allowing the heel to lift off the support platform during plantar flexion, reinforcing proprioception of spasmodic or voluntary plantar flexion and consequential heel lift.
3. The foot support should maintain alignment of the foot with the knee joint, resisting spasmodic inward rotation of the foot about the tibial axis.

Weight bearing support specification:

1. The weight bearing support should allow 70^{circ} of hip extension from an at rest 90° femur/trunk angle during sitting.
2. The weight bearing support should be comfortable and distribute pressure over the weight bearing surfaces.
3. The weight bearing support should not impede spinal extension.

Head support

1. The head support should enable the occupant to maintain head alignment when at rest, and should not strongly resist neck extension or axial rotation during spasm.
2. The head support should be able to support the head through either occipital or suboccipital contact depending upon the needs of the occupant.

   NOTE: It was decided not to design a dynamic head support to complement the dynamic seat as it was considered that there was insufficient time and resource available within the project grant for the research team to complete this work. See Chapter 12 for a description of undergraduate work that the author supervised in this area.

Following definition of this specification, detailed design of the first independent seat was commenced. The design of this seat is described in Chapter 10. The author's reflections on the evaluations and his initial thoughts on this design are given in Figure 9-8.

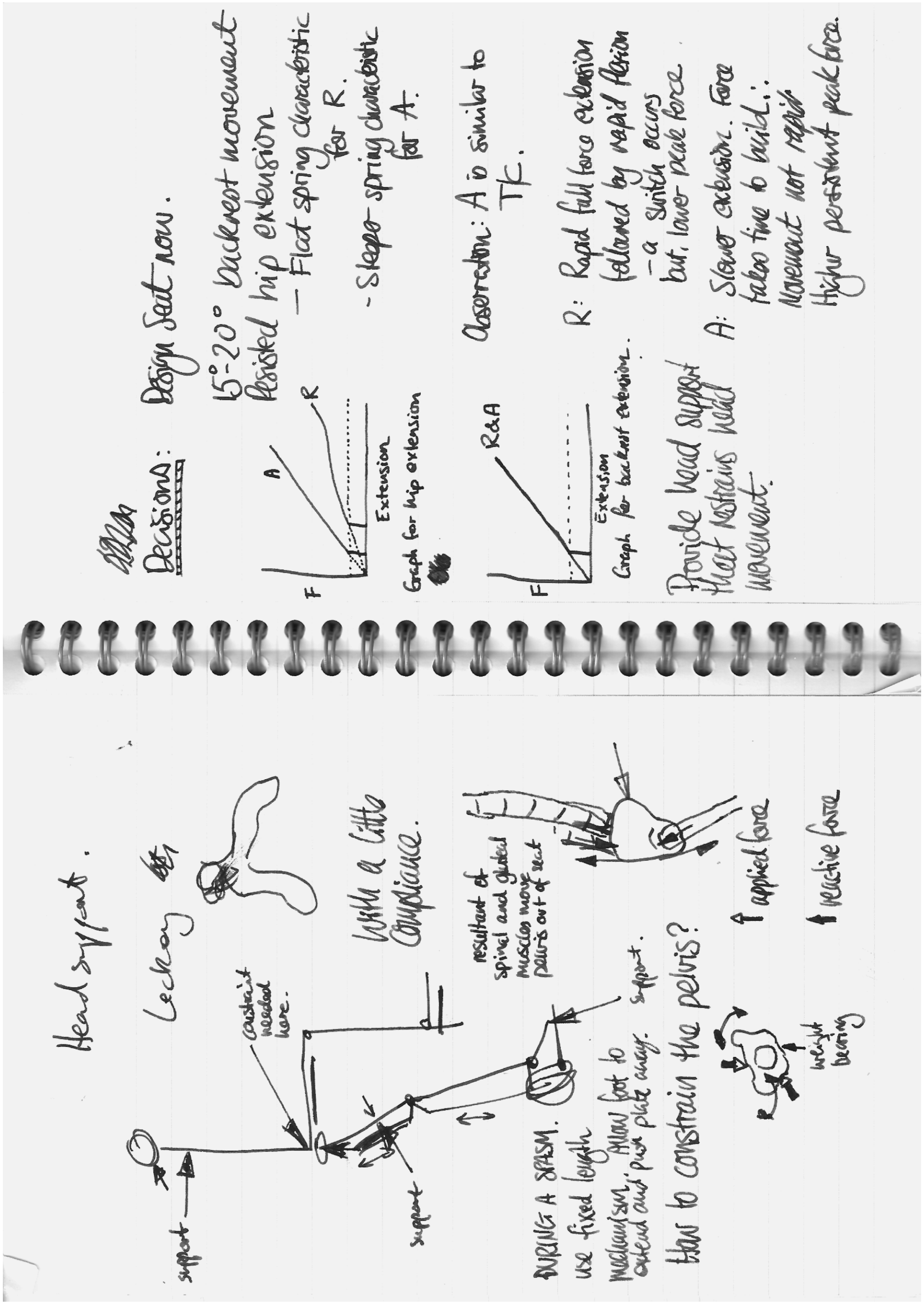

Figure 9-8: These drawings show sketches in the author's notebook describing reflections on the semi-soft evaluations with A1 and R1. Key issues that have arisen are constraint of the pelvis, spring characteristics, and mechanism design.

Chapter 10

Design of a Fully Independent Dynamic Seat

This chapter describes the design of the first of two fully independent dynamic seats following principles investigated using soft and semi-soft prototypes. The soft and semi-soft prototyping methods used for the investigation of early stage prototypes are described in Chapter 4; and the semi-soft prototype is described in Section 9.3.

There were three principles behind the design of this seat:

1. *Compliance:* The seat should allow the occupant to experience a spasm, without resisting the movements of the spasm. The occupant should not experience an end-stop in the movement. It should return the occupant to the neutral position at the end of the spasm.

2. *Comfort:* The seat should be comfortable and reduce the pressure applied by support surfaces, straps and other constraints as far as possible.

3. *Function:* The seat should enable the child to be as functional as possible. It should prioritise stabilisation of the head and shoulders, assisting the child with maintaining eye contact and hand position.

10.1 Inventing a seat: Observation and Inspiration

The challenge faced with the design of this seat was to implement the support scheme tested in the semisoft prototype (Section 9.3) without needing intervention from a supporting team to provide the necessary dynamic characteristics. Thus the seat needed to:

1. Provide appropriate postural support for the occupant;

2. Maintain good alignment of the occupant's skeleton;

3. Not injure the occupant or cause discomfort beyond that experienced by the occupant in his usual seating;

4. Be safe for use by school staff;
5. Allow independent movement of each leg against a variable preload and spring rate;
6. Allow independent movement of the backrest against a variable preload and spring rate;
7. Allow measurement and recording of applied torques and angular positions for subsequent analysis;
8. Stabilise the occupant's head and shoulders by prioritising movement in the leg supports rather than the backrest.

This novel seat concept was inspired by observation of R1 being held securely and comfortably by his mother. In particular, inspiration for the new seat was derived from:

1. *Observation of how R1's mother supported him during the initial soft prototype evaluation.* She carried him facing forwards, held with his back against her front, with his weight borne by her arms beneath his legs, which were held in a flexed position.
2. *By considering the reasons for seating a child.* Sitting in itself was not the aim of this research. The main aim is provide support for the child that enables him to be comfortable, to be socially engaged, and to participate in table-top activities.
3. *By applying a simple change to the fixed datum used when thinking about a child experiencing a spasm.* Most seating takes the thigh of the child as a datum, with the backrest and foot position moving relative to this fixed segment. Conceptually, the new seat uses the head as a fixed datum, with all other parts of the body being moveable relative to the head.

When these support concepts and objectives were developed into a design concept, they resulted in a structure that was more akin to an exoskeleton than a seat.

10.2 Design Concept

The design of the this seat was invented during the soft prototype evaluation conducted in R1's own home after the first evaluation of the previously described linked seat, and was inspired by observation of R1's mother when she held him against herself, facing forwards (away from her body), slightly prone and with his hips flexed to about 70° (See Section 8.1.2). She supported his weight with an arm underneath his thighs, and another across his chest. In this position she was able to allow his spasms to occur, absorbing most of the hip extension in his legs; while maintaining a stable head position. This enabled R1 to maintain eye contact and head stability during a spasm. His mother also reported that he experienced fewer spasms in this flexed position, which was similar to the hip-flexed position she placed him in when sitting on her lap. He seemed to enjoy 'sitting' while supported against his mother's body. He was secure, stable, and the physical disruption caused by his spasms was minimised.

Evaluation of the soft and semi-soft prototypes showed that if movement was allowed at the beginning of a spasm, and the spasm was not opposed with a solid stop, then the spasm forces were reduced. This is the core principle upon which this dynamic seating design has been based.

In the soft prototype evaluation, R1 could be held by his mother and the project team in such a way that his weight was supported, his legs were able to move to a fully extended position during a spasm, and his pelvis was able to tilt forwards as his spine extended. This movement pattern and the support required to enable him to remain stable and oriented during a spasm was implemented in the semi-soft independent seat prototype and then in the fully independent seat prototype. Some early sketches of this seat can be seen in Figure 10-1.

10.3 Mechanism Design

The seat had a dynamic backrest and separate dynamic leg supports. Each of these segments was designed to be able to move independently of the others, with independently controlled spring parameters and geometry. In summary, the seat consists of two independent leg supports, a backrest and a head support, mounted on a frame, which is in turn mounted on a standard height adjustable mobile base. The leg supports provided support at the foot and thigh, and were jointed at the knee and hip. The backrest provided support to the spine and the head, and was jointed behind the sacrum. The child's weight was borne by a bicycle saddle position behind and between the leg supports, and below and in front of the back support. Each of the mechanism components is described in the subsections below.

The diagram in Figure 10-2 shows the support scheme provided by the first and second independent seats.

A diagram of the seat taken from the CAD model (without bought in head support or straps) is shown in Figure 10-3. Though this seat was complex, all adjustments could be carried out with a 6mm Allen Key, except for the head support, which required a 3/32" key as it was a bought-in product from the United States.

10.3.1 Leg Supports

The leg supports were hinged on an axis through the hip joint, and could be adjusted for width (across the hips), abduction, and hip axis position. The full range of adjustment for this element is shown in Figure 10-4.

The hip spring system was designed to provide a linear increase in force as the leg support is deflected, and included compensation for the varying effect of self-weight on the torque as the leg support deflected. Adjustment was provided for initial tension and spring rate. The cable linked system also allowed the child to flex his hips to a hip angle of less than ninety degrees, however no resistance or assistance was provided to this movement beyond gravity acting on the leg and the seat. Child R1's spasm pattern was of alternating extensor and flexor spasms, so this flexor movement was important for him.

Kinematic Parameters

These adjustments allow the seat to be fitted to the legs and hips of the occupant for size; the protection of the hip joints from dislocation through positioning; and the adjustment of joint angles to modify spasm initiation sensitivity.

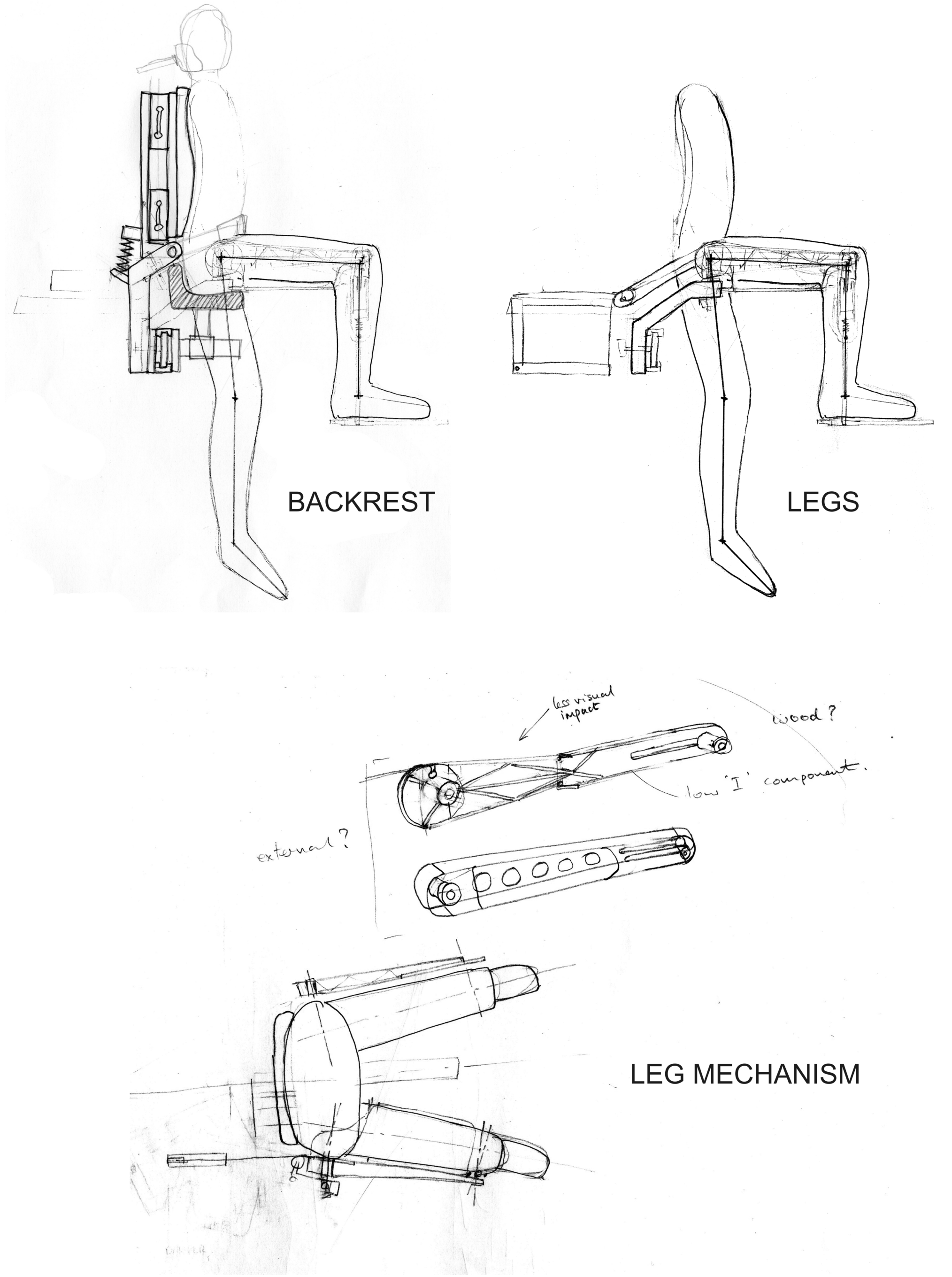

Figure 10-1: Early design sketches for the first independent seat showing the leg and back support concepts. The spring frame orientation was changed for this design from vertical to horizontal action, and the number of load cells in the backrest was reduced to one because of the additional channels was needed to capture independent hip and knee joint motion. At this stage, the visual impact of the seat was also being considered, however the team decided to build a functional non-aesthetic seat at this point to reduce the time to validation of the concept in a longer-term evaluation.

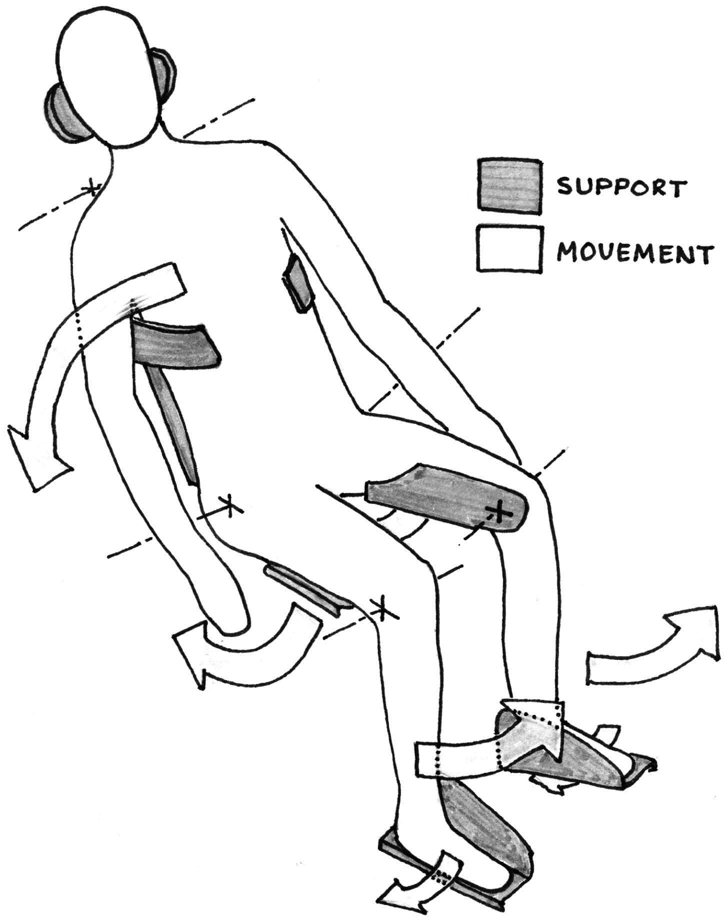

Figure 10-2: A diagram of the support scheme provided by the independent seats, showing the rotational axes and the regions of support.

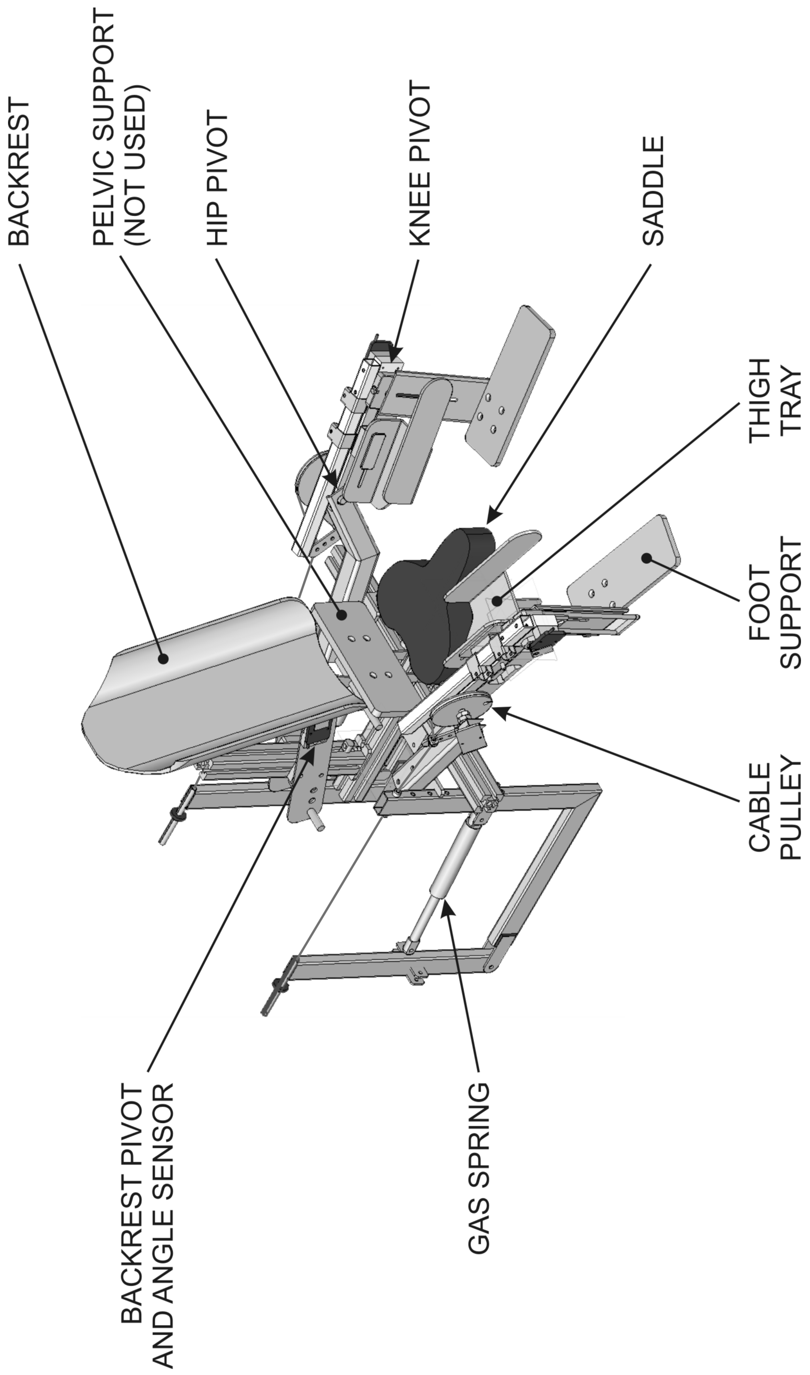

Figure 10-3: A diagram of the first fully independent seat showing the independent leg supports, the spring mechanism and the backrest. The bought-in head support (Stealth i2i / Stealth Combo), footrest springs and straps are not shown as these were not modelled when the seat was designed. Though this seat was complex, all adjustments could be carried out with a 6mm Allen Key, except for the head support, which required a 3/32" key as it was a bought-in product from the United States.

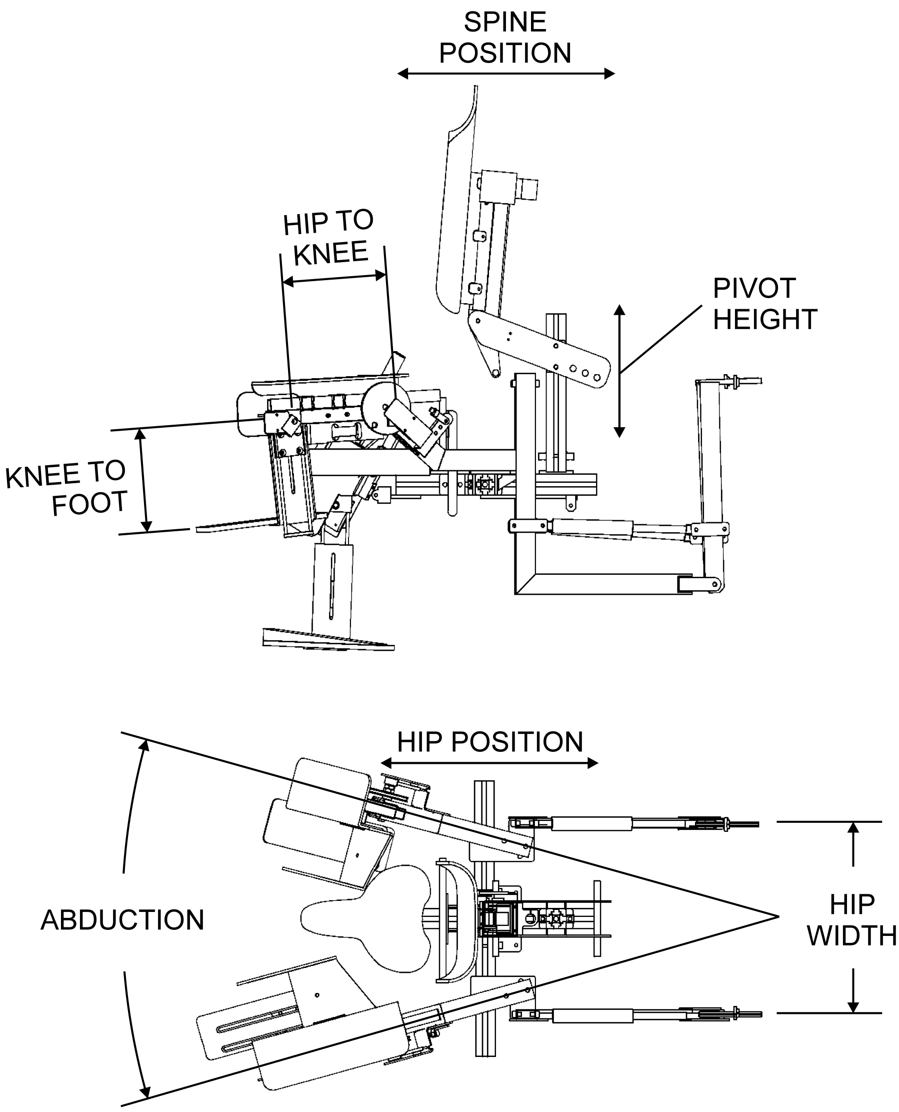

Figure 10-4: A diagram showing all the positional adjustments possible on the leg and backrest mechanisms of the first fully independent seat.

1. *Hip Abduction Angle* was adjustable between 0° and about 30°. This adjustment was included because observation of the R1 and A1 in their conventional seating, and experience positioning them by hand on saddle seating showed that a small degree of abduction seemed to stabilise the children and reduce their sensitivity to spasm initiation. Previous experience (described in 6 also demonstrated the benefit of imposing some abduction. This adjustment was achieved through sliding and rotating joints between the leg assemblies and the main frame.

2. *Hip Width* adjustment was necessary to comfortably fit the seat to the child. Proper alignment of the child's thighs with the leg gutter supports required that the spacing of the leg supports was adjustable. This was achieved through sliding joints between the leg assemblies and the main frame.

3. *Hip Joint Position* was adjustable by moving the hip hinges forwards or backwards. This adjustment was necessary to achieve correct alignment of the seat hip hinge with the child's hip joint. This adjustment was implemented using a lockable sliding joint between the leg assemblies and the main frame.

4. *Hip Flexion Angle (at rest)* adjustment was included to allow compensation for small amounts of spring deflection and backlash in the mechanism, enabling the leg supports to be leveled. Later it was also used to induce small amounts of initial hip flexion in the child as this was found to reduce spasm initiation sensitivity. Adjustment was achieved by shortening or lengthening the spring cable with a screw adjuster built into the spring frames.

5. *Axial thigh rotation* was controlled by a strap originating beneath the thigh on the inside leg, which passed around and over the thigh, and was fastened to the outside face of the hip support. This strap applied some external rotation to the femur, helped to maintain hip alignment and retain the leg on the thigh support. It was adjusted so that the thigh was securely held, but was not compressed.

Dynamic Parameters

These adjustments define the dynamic response of the leg supports to hip extension, as well as the firmness of the leg support when a spasm is not in progress.

1. *Hip Spring Initial Tension* adjustment was required to enable the initial torque threshold to be set. If the leg supports were too soft initially (before the onset of a spasm) the children were less settled in the seat. This threshold was set low enough for the seat to respond quickly if a spasm occurred, but high enough that the seat would feel stable and secure in the absence of a spasm. The initial tension was adjusted by modifying the pressure in the gas spring. This pressure could only be adjusted downwards by venting small amounts of gas from the spring.

2. *Hip Spring Rate* was the most important dynamic adjustment, and the children were sensitive to its variation. The semi-soft evaluation showed that if the spring force rose too quickly (the spring rate was too high), then the child's spasms escalated in intensity against the resistance

of the springs. If the spring rate was too low, then the child felt insecure and large and rapid movements occurred, which ended when the leg supports hit their end stops. This sudden stop also caused a sudden undesirable intensification of spasm force. The end stop induced force peak was later measured with the instrumented seat. The chosen spring rate was low so that once movement of the leg supports started, little additional resistance was felt by the occupant as the spasm progressed. This characteristic was selected as a result of observations made of the effect of spring rate variation during the semi-soft evaluations. To achieve a low spring rate in a compact package and still have capacity for the required force, a variable pressure gas spring was used.

The spring mechanism also accounted for the reduction in gravity induced torque on the leg as the leg rotated and moved closer to the pivot point, and maintained a linear response to the spasm. This was achieved through the use of a circular pulley with its centre offset from the centre of rotation.

10.3.2 Foot Supports

The child's feet were supported by dynamic foot supports mounted to a pair of bars hinged approximately coaxially with the child's knee. As with other areas of the seat design, the soft and semi-soft evaluations provided useful insight that guided the design in this area. It was found that over-constraint of the child's feet, and particularly pressure on the soles of their feet, caused their sensitivity to spasm initiation to increase. It was necessary to maintain some support of their feet to protect hip alignment and also to provide a weight bearing surface for the legs to reduce pressure on thighs. The foot supports were also designed to provide proprioception of spasm movement. This was achieved by removing contact with most of the sole of the foot during a spasm and reestablishing contact after a spasm, as would occur if a child stood on tip-toe. It was also important that the foot supports maintained support and alignment of the foot during spasms, but that whilst doing so they did not apply large forces.

The foot supports consisted of a rigid flat platform mounted on the side of a vertical linear slide that was hinged through the knee joint. The platform was sprung from below with compression springs, and was free to move downwards along the slide against the spring force. The child's foot (wearing a shoe) was constrained onto the platform with a strap across the foot at the base of the toes. A second strap which was anchored underneath the the platform at the same point as the toe strap, passed around the back of the child's foot. This strap prevented the foot from leaving the toe strap, but did not prevent the heel from lifting during a spasm. See Figure 10-5.

Kinematic Parameters

These adjustments are present to enable the foot to be secured to the foot support, maintaining alignment and allowing additional proprioception of spasms.

1. *Tibial length* was adjustable by the vertical position of the foot support on its slide. This adjustment allowed the foot support to be adjusted for tibial length without modifying the spring characteristics. If the spring characteristics were modified by changing the springs installed or introducing an initial compression, then it allowed the original tibial length to be restored.

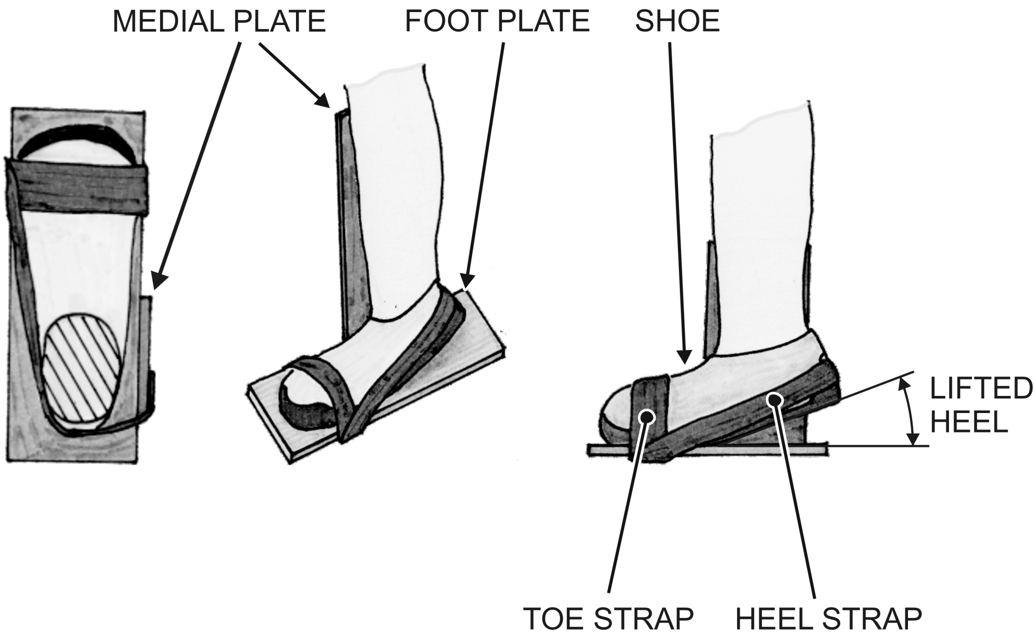

Figure 10-5: A sketch showing the foot support and restraint scheme. This design was carried through into the second fully independent seat. The toe strap holds the forefoot onto the plate. The heel strap maintains the forefoot under the toe strap and the medial side of the foot against the lateral support, but allows the heel to lift during a spasm.

2. *Heel and toe strap length* were both adjustable to ensure that the child's foot could be made secure on the foot supports. The toe strap holds the distal portion of the foot onto the foot support; and the heel strap prevents the foot from backing out of the toe strap, whilst still allowing the heel to lift off the foot support during a spasm.

Dynamic Parameters

These parameters provide for the adjustment of the pressure of the foot support on the sole of the foot before and during spasms.

1. *Foot support spring rate:* The spring rate was set through the selection of the springs installed and was not changed. It was not found to be critical.

2. *Foot support spring preload:* The spring preload was adjusted by raising the initial position of the footrest beyond the sole of the child's shoe when at rest, creating some initial compression. The springs were changed once at the beginning of the evaluation with A1 as they were initially not strong enough to maintain sufficient contact with his foot when he was at rest while allowing sufficient movement during a spasm. Longer springs were installed which allowed an increased preload while maintaining spring rate.

10.3.3 Backrest, Lateral Thoracic Supports and Head Support

The backrest and head support were also part of the dynamic mechanism of the seat. They were both mounted on the single instrumented backrest mount, which was adjustable for position in the sagittal plane. The backrest plate (a Stealth Icon 12" Tall Backrest) which was behind the cushion was adjustable up and down, to suit the child. The backrest mount also had two adjustable dynamic parameters: spring rate and spring pretension.

The head support was mounted on an off-the-shelf jointed arm fixed to the rear of the backrest mount. Two different head supports were used for the two children on which the seat was evaluated, because their needs were different. These two supports were:

1. *Stealth i2i Small* – this is a head support that also has two 'arms' that come down and forwards over the child's shoulders. This prevents a very mobile child from getting caught behind or under the support. It was used by child A1. A sketch of the i2i support is shown in Figure 10-6.

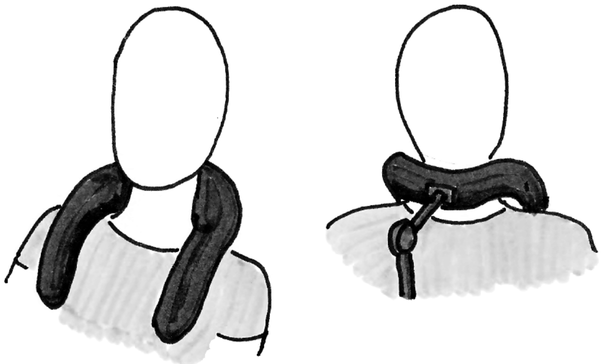

Figure 10-6: A sketch of the Stealth i2i head support as used on the first and second fully indepenedent seats. The 'wings' on the side of the support prevent the child from falling forwards or sideways out of the support.

2. *Stealth Combo Small* - this is a more conventional occipital head support with lateral 'wings' to enable the child to keep his head facing forwards more easily. It was used initially by child R1, however this support proved unsuitable and the head support from his usual seat was transferred to the dynamic seat.

The backrest frame also had a pair of lateral thoracic supports fitted to provide lateral truncal stability for the child. They contributed to the child's security when seated as they extended partially around the chest of the child. A chest belt was fitted across the front of these supports to prevent the child from falling out forwards.

Kinematic Parameters

These parameters are adjustable to fit the seat backrest, head support and lateral supports and to the child; and to modify the movement geometry for best comfort and function.

1. *Backrest Position* adjustment was provided to enable the backrest to be fitted to the size of child, and also to enable adjustment of the lowest point of support. Because of the geometry of the backrest hinge point, when the backrest pivot point was high, then the lower portion of the backrest below the pivot point moved *forwards* as the backrest reclined. For this reason the ability to move the backrest upwards on its mount was included, removing or reducing the forward motion component.

2. *Backrest Hinge position* was adjustable in two axes – forwards and backwards to accommodate different body thicknesses, and up and down to enable alternative hinge positions to be explored. It was not known whether it was best to hinge the back support below, at, or above sacral height, as back movement occurred as a result of hip extension and spinal extension in the soft and semi-soft evaluations.

3. *Lateral Support Position and Orientation* adjustment was possible in two linear axes and around four rotational axes. The lateral support pad was mounted with a ball joint on the end of a multi-link jointed arm. The arm was fixed to a swing-away clamp mounted on a pair of vertical tubes on either side of and just behind the seat backplate. This arrangement allowed the lateral supports to be positioned and orientated to closely fit the occupant's thorax (chest area), providing stability and security. The supports needed this degree of adjustment because of variability in body shape between children, and the adjustability of the seat back position.

4. *Head Support Design and Position* was chosen to suit individual children, as their needs were very different. The head support selection was not made for each child until after an initial one day evaluation made before the main week long evaluation. Both head supports were adjustable in position and orientation in a total of five axes. The adjustment missing was lateral translation. All five degrees-of-freedom were used when positioning the head supports for both children, but particularly child R1.

Dynamic Parameters

The dynamic parameters of the backrest are adjustable to enable balancing of the thigh and back reactions to the hip extension torque, and also the dynamic profile of the response of the backrest to a spasm.

1. *Backrest Spring Initial Tension* adjustment was required to set a torque threshold below which movement would not occur. As with the hip supports, this threshold gave a feeling of security for the occupant. This adjustment could also be described as a torque range offset, as it increased the backrest torque at minimum and maximum extension. Experimental work with the semi-soft prototype showed that this adjustment was necessary. If the backrest threshold was set too low, then the seat felt insecure and too much disorienting movement occurred early in the course of the spasm, or even during non-spasmodic movement. If the threshold was set too high, then the backrest would not move sufficiently during a spasm and the spasm would intensify. Too high a threshold caused the spasms to rapidly intensify early in their course, especially if the hip preload was also too high.

2. *Backrest Spring Rate* adjustment was required because during the soft and semi-soft prototype evaluations it was found to affect the progression of a spasm in a similar way to the adjustment of the initial tension. If the spring rate was set too low then the spring would not sufficiently resist the spasm movement as the spasm progressed. Hip extension would be expressed through backrest movement rather than leg movement, and the backrest would hit its end-stop. The spring rate had to be balanced to allow sufficient movement to accommodate the spasms, but also to cause most of the hip extension to be expressed through leg movement. These characteristics resulted in the use of conventional helical extension springs rather than gas springs as used for the leg supports.

10.3.4 Weight-bearing saddle

The weight of the child sitting in the seat was borne by a bicycle type saddle (mounted to the seat frame), and the leg supports. When sitting, most of the child's weight is borne by the saddle, with the weight of the legs being supported by the thigh and foot supports. When a spasm was in progress, some of the support of the child's weight shifts from the saddle to the leg and foot supports; and a little from the saddle to the backrest.

The saddle was attached to a vertical tube that was secured in a vertical clamp on the front of the seat frame. It was adjustable in height and rotation about a vertical axis, though in practice only the height adjustment was used.

1. *Height adjustment* on the saddle was part of the hip joint alignment adjustment. Horizontal alignment of the hip joints of the child with the seat hip hinges was achieved with the adjustment of the leg supports on the seat frame; and vertical alignment was achieved through adjustment of the saddle.

10.3.5 Seat Frame and Base

The seat was mounted on a frame attached to an off-the-shelf mobile seat base.

Seat Frame

The seat support assemblies were mounted on an adjustable frame, which was in turn mounted on a Jenx Gamma height adjustable seat base. The frame was built from 40mm x 40mm aluminium extruded sections from the Bosch Rexroth frame building system. The frame consisted of a central horizontal spine, with two lateral horizontal arms on which the leg assemblies were mounted. The saddle and backrest assemblies were mounted on the central spine.

Each of the lateral arms was adjustable forwards and backwards on the central spine. They were attached to the spine at 90°. The leg assemblies could be adjusted towards and away from the midline by sliding them on the lateral arms.

Seat Base

The whole frame and seat was mounted on the top plates of a Jenx Gamma mobile indoor base. The base was chosen because it did not have any handle attached to the frame behind the seat mounting plate

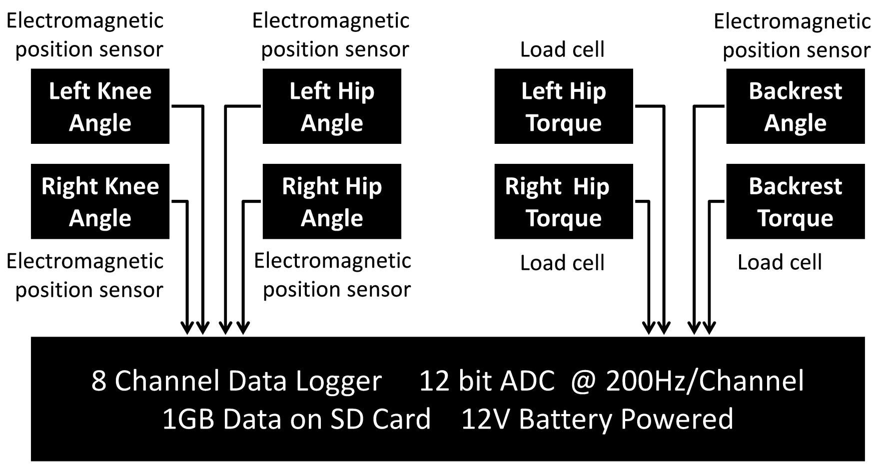

Figure 10-7: A block diagram of the sensor and data logging system installed in the first independent seat.

which would have obstructed the dynamic seat backrest.

The base is designed to permit adjustment of an attached seat in height and anterior / posterior tilt. Height adjustment is achieved with a small foot operated hydraulic jack built into the lifting mechanism. Tilt is achieved through the horizontal axis pivots on the mounting plates, and a lockable gas spring anchored below the pivots and to a point on the frame about 100mm from the pivots. As a result the seat can be tilted to any desired angle between about 10° forward and 30° back. The gas spring counterbalances the weight of the seat and also damps the movement, preventing any sudden changes while a child is in the seat.

The seat base is fitted with castors which permit it to be moved around the school where it is used, however it is designed to be used indoors and is not suitable for uneven outdoor surfaces.

10.4 Instrumentation

The seat was instrumented with torque and position sensors installed across each joint. The sensors allowed precise measurements to be made of the torques applied to the seat by the occupant. Each sensor channel was plugged into a compact battery powered data logger that sampled the data at 200Hz / channel in 12 bit resolution (see Table 5.2). A block diagram of the sensor and data logging system is shown in Figure 10-7.

10.4.1 Torque Measurement

Torque was measured using the Tedea Model 1042 (75kg) load cells from the previous seat. These cells were designed for weighing applications, were affordable, and had excellent linearity, even with loads applied up to 200mm off-axis. They were mounted in the leg and backrest mechanisms at a known distance from the pivot point in such a way that the mechanism applied a pure load and no torque to the sensor. The load cells were mounted to measure the torque applied to the backrest or foot supports of the seat.

Backrest torque measurement

The backrest torque was measured by a load cell embedded in the backrest mechanism. The load cell was interposed between the backplate and head support mount lever, and the lever to which the springs were attached. The spring lever and the backplate mounting lever shared a common pivot axis. As with the leg supports, the load cell was mounted in such a way that it was protected from off-axis torques and loads, being screwed to the spring lever, and pin-jointed to the backplate and headrest mount. The slotted pin joint permitted both the spring lever and the backplate lever to deflect slightly under load without inducing unwanted strains in the loadcell. Unlike the previous linked seat, which did not measure head support torques, extensor torques applied to the head support were measured by the load cell. See Figure 10-8 for a diagram of how the backrest load cell was mounted.

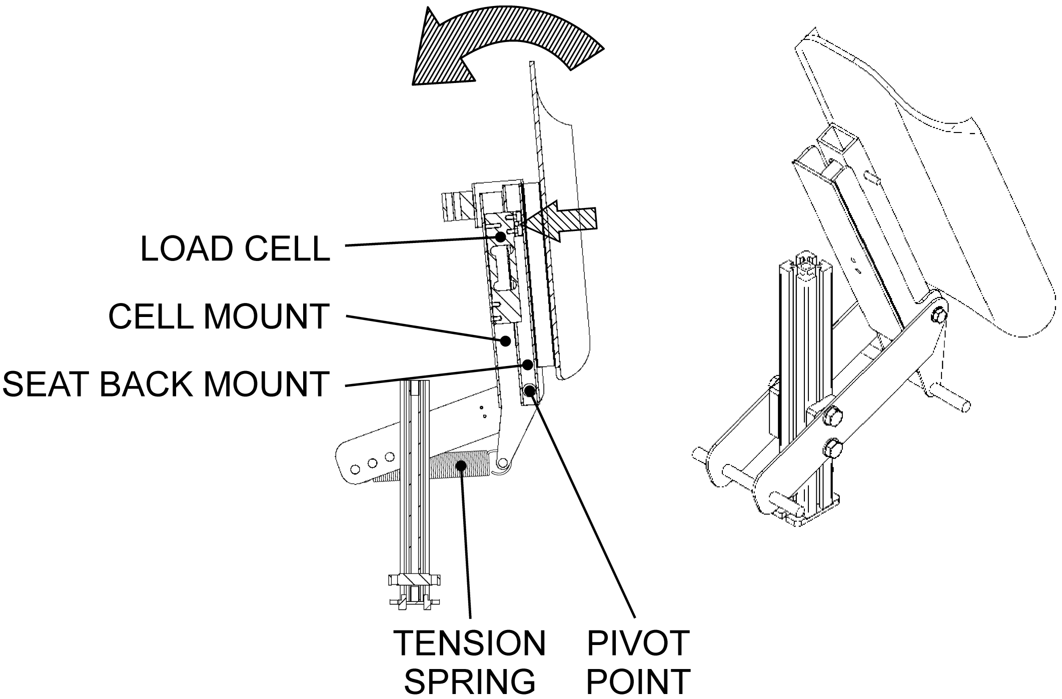

Figure 10-8: A diagram of the backrest load cell mount on the independent seat, showing the mechanism that causes the cell to measure applied torque rather than force. The load cell sensing position was mm from the backrest pivot point.

Leg torque measurement

Leg torque was measured by a load cell embedded inside the leg support mechanism. The cell was slightly modified to allow it to be mounted on the same side of the sensor at each end, rather than on opposite sides as would usually be the case. It was rigidly screwed to a short arm that was attached to the spring pulley that transferred the spring force to the thigh support. The other end of the load cell was attached to the thigh support arm. This mount was not rigid. The load cell was constrained to the arm with a screw and a flexible mount fitted into a hole bored into the load cell. The arm, made of 1" square box section steel, was attached with a screw and two rubber 'O' rings. The screw was not torqued tight, but was tightened down until the 'O' rings just made contact with the steel components. The 'O' rings introduced compliance into the system, substantially reducing any unwanted torques that might have been applied to the sensor due to slight unintentional misalignment of the two arms, or structural deflections caused by the applied loads. See Figure 10-9 for a diagram of how the hip joint load cell was mounted.

10.4.2 Angle Measurement

The angle of each moveable joint in the seat was measured with the electromagnetic blade sensors from Gill Technology that were used in the previous seat. These compact sensors measure the linear or rotational movement of a 'U' shaped piece of steel (the actuator) that passes over and either side of the thin rectangular sensor. The voltage output from the sensor varies between 0V and 5V depending on the position of the actuator. The sensors provide a voltage output that changes proportionately with position. They have an excellent signal to noise ratio, and because they are non-contact sensors, they are reliable for millions of cycles. To achieve sufficient range of motion, the sensors were positioned with the steel actuator close to the centre of rotation. A diagram of the sensor positioning for the knee and hip joints is shown in Figure 10-10

10.4.3 Data logger

The data from the load cells and position sensors was logged to a battery powered stand-alone data logger. The data logger (a Dataq DI718b) had eight channels, all of which were used. It was capable of sampling 12 bit data at up to 1200Hz for a single channel, or 200Hz per channel if measuring eight channels simultaneously. It had 1GB of storage available using an SD memory card. The signal conditioning of the data logger was modular: for this research, five 0-5V channels and three strain-gauge bridge channels were installed.

Cables from the sensors were gathered together in an interface box, which also provided power for the data logger. The interface box was provided with a 12V dc power supply from a 12V lead-acid gel battery. Using battery power freed the seat from a mains power supply requirement, and made it so that no further intervention was required from the therapists or parents once the data collection had been started.

Data from the data logger was retrieved from the memory card and uploaded to a computer. 'WinDaq Waveform Browser for SD' software on the computer was used to view the data and to apply appropriate calibrations for each of the sensors. The seat was calibrated for torque by applying a known torque to the legs and backrest with the 'force applicator' built for the project (See Figure B-9) and then entering the known values into the data logger software calibration tool, which scaled and offset the inputs

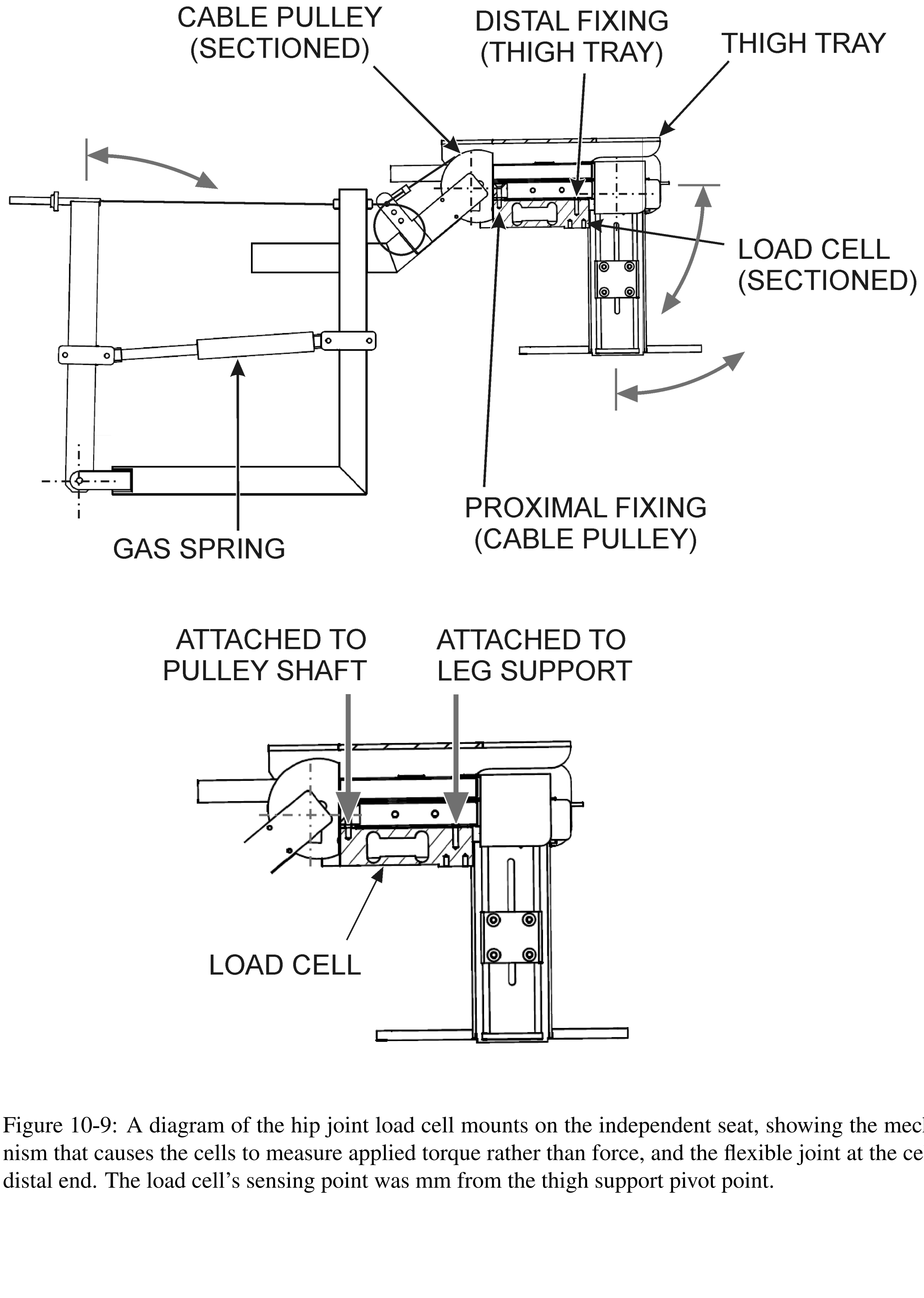

Figure 10-9: A diagram of the hip joint load cell mounts on the independent seat, showing the mechanism that causes the cells to measure applied torque rather than force, and the flexible joint at the cell's distal end. The load cell's sensing point was mm from the thigh support pivot point.

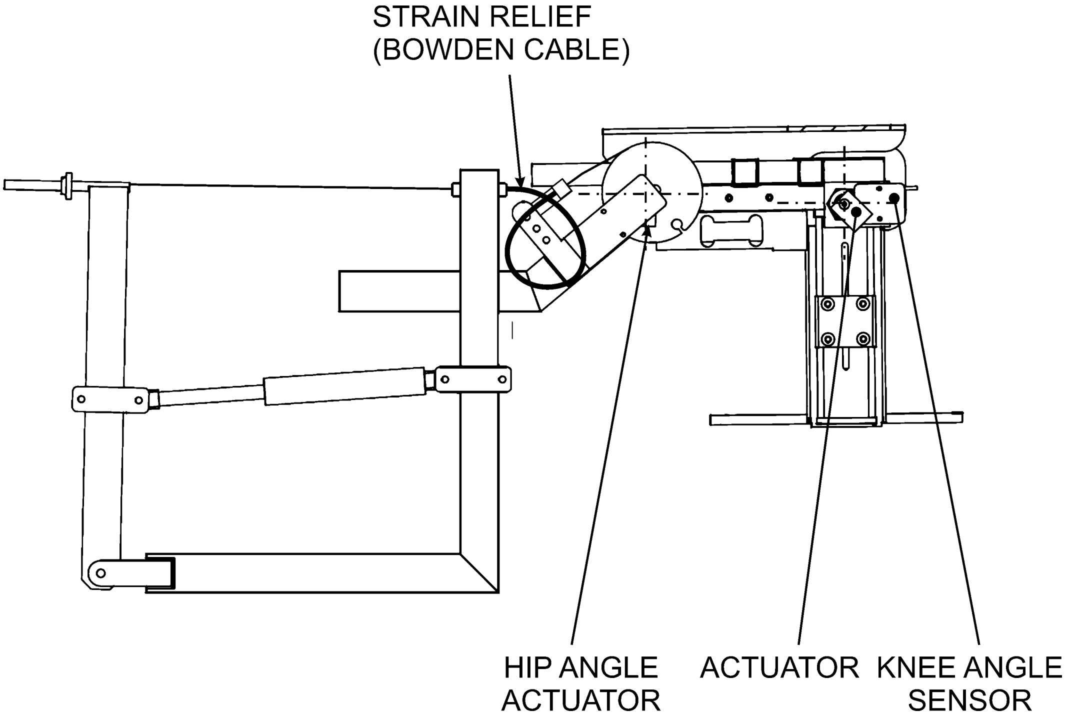

Figure 10-10: A diagram of the positioning of the electromagnetic angle sensors on the independent seat leg supports. The actuators rotate with the joint, while the sensors remain stationary, reducing the risk of sensor cable conductor breakage.

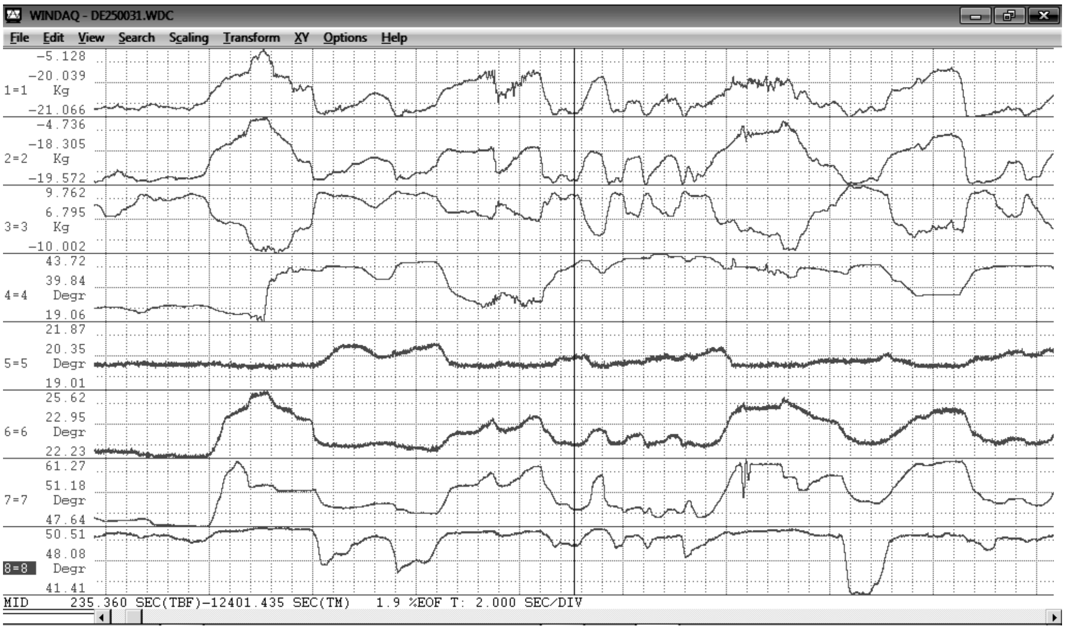

Figure 10-11: A screen capture from the WinDaq software used to calibrate and initially analyse the sensor data. This data is from 30^{th} November during A1's 2010 evaluation of the independent seat and is not yet fully calibrated.

appropriately. Forces could be applied with a tolerance of $\pm$2N. The angle sensors were calibrated with a goniometer. Tolerance on the angle measurements was $\pm$0.5 degrees.

Once calibrated, the data was exported to Excel for plotting and analysis. Figure 10-11 shows a screen capture from the WinDaq software.

10.5 Construction and Risk Assessment

The first independent seat was manufactured by an experienced technician at BIME and risk assessed by the author. The design, manufacture and risk assessments were confirmed by the BIME principal engineer.

Chapter 11

Independent Seat Evaluation

The first independent seat prototype was evaluated by Child A1 and Child R1. This evaluation had two objectives. The primary objective was to provide user and therapist feedback on the design of the independent chair; and the secondary objective was to collect data on the child's spasms from direct measurement using the instrumented chair, from direct observation, and from analysis of video.

Following experiences with previous evaluations where necessary modifications became clear within a few minutes of testing the seat and prolonged evaluation was not possible because of the seat's unsuitability in its unmodified form, a two stage incremental evaluation process was chosen that would not put undue pressure on the child and the evaluation team, but would allow the seat to be modified to make it as comfortable as possible for the child before he needed to spend prolonged periods of time sitting in it.

It was planned that the evaluation would be carried out in three stages for each child:

1. A short one day evaluation to check the seat configuration and enable minor problems to be rectified.

2. A week long evaluation to collect data on spasms and assess the immediate impact of the seat on the children. This evaluation is primarily to confirm the appropriateness of the design.

3. A one month long evaluation to collect data on spasms and assess the medium term impact of the seat on the children, including any changes in their posture and movement patterns.

A gap of nearly two weeks was placed between the first two evaluations for work to modify the seat that was identified during the short evaluation.

Each evaluation approximately followed the method below:

1. The seat was assembled and prepared for use by the child concerned as far as was possible with the information available.

2. The detailed plan for the evaluation was discussed with the local clinical team.

3. The video cameras were set up in place ready for recording.

4. The child was brought into the room.
5. The sensors and cameras were switched on.
6. The child was transferred into the seat.
7. The child was observed for a short time, and reassured when necessary.
8. In the case of the evaluations with R1, problems with the seat became evident very quickly, and their effects and the effects of previous modifications were recorded.
9. For A1's medium term evaluation, the seat was used as his every-day seat, and he was transferred into it ready for classroom activities in his usual way, without a period of formal observation.
10. The evaluation sessions were terminated either because the child became too distressed, their objectives were achieved, or the time available for the session had expired.

The following pages are a tabulated summary of the evaluation's findings, and then a detailed description of each session. In the summary table, the people present for the evaluations are coded as follows: EN = Research Engineer, OT-R = Research Occupational Therapist, OT-S = School Occupational Therapist, T = Teacher, TA = Teaching Assistant, PT = Physiotherapist, P = Parent.

A SUMMARY OF THE EVALUATIONS OF THE FIRST INDEPENDENT SEAT FROM NOVEMBER 2010 - JANUARY 2011

Evaluation	**1**	**2**	**3**
Present	A1 / EN, 2xOT-R, T, OT-S, TA	J1 / EN, P	A1 / EN, 2xOT-R, T, OT-S, TA
Date	11/11/2010	15/11/2010	24/11/2010
Duration	1 day	1 hour	6 days
Objective	Overall seat evaluation prior to longer term evaluation at school	Comfort checking with verbal more able child (also with cerebral palsy)	Medium term evaluation of seat in everyday use in a classroom context
Location	School	BIME	School
Findings	+ Child A1 sat comfortably, lumbar contact restored. + Child experimented with voluntary seat movement. + Planning resulted in a calm and orderly evaluation. ~ Constant pressure on abductor plates. - Head support insufficient. - Problem identified of backrest shear due to pivot point. - Minor dimensional changes needed for comfort.	+ J1 played in the seat and + reported that it was comfortable - shear issue with backrest confirmed	+ voluntary cycling movements observed + used the seat tray to maintain upright head position + responded well to music + sat in the chair comfortably for prolonged periods + no skin reddening from pressure ~ anterior chest support needed due to low tone of A1 between spasms - shear issue remained - it was not possible to address this without a substantial redesign of the backrest mechanism.

EN = Research Engineer, OT-R = Research Occupational Therapist, OT-S = School Occupational Therapist, T = Teacher, TA = Teaching Assistant, PT = Physiotherapist, P = Parent

4	5
R1 / 2xEN, OT-R, P	R1 / EN, 2xOT-R, T, TA, PT, OT-S
17/12/2010	10/01/2011
2 hours	5 days
Short evaluation with R1 prior to medium term evaluation in	Medium term evaluation in classroom context
Great Ormond Street Hospital	School
+ head control improved. R1 demonstrated independent head positioning for short periods. + R1 seemed to enjoy sitting in the seat and explored the movement it afforded him. ~ head support is critical - R1 needed occipital or suboccipital support. ~ anterior chest support needed due to low tone between spasms.	+ R1 sat comfortably in the seat on some occasions when his tone was low. + R1 used the seat for table-top activities. + A tray or table top improved R1's head control ~ R1 was very different in the seat to his previous evaluation. ~ Movements were very asymmetric, with LHS stronger than RHS. ~ underlying tone was variable, resulting in varying requirements for postural support. ~ when R1 was hypotonic, transfer was easily achieved with two people - Ease of transfer into the seast was variable and required two or three people, depending upon R1's underlying tone and emotional state. - R1 was initially distressed on being placed in the seat. - R1 was bridging on the front edge of the saddle and the backrest (with its high pivot point), and pushing on the pelvic strap. This resulted in reddening of ASISs under pelvic strap.

CONCLUSIONS
This series of evaluations yielded several key findings: 1. A child's emotional and health status significantly influences his spasm intensity and frequency. 2. Children may have some ability to voluntarily moderate their spasms. 3. The seat backrest should be hinged through the hip joint axis. 4. Spring stiffness should be variable through a wide range, but exact values are not critical. 5. Anterior thoracic support is likely to be needed to provide support to a child with low background tone. 6. Children experimented with the voluntary movement the seat afforded them, using both leg and backrest movement. 7. Use of the seat in the classroom requires that transfers can be easily accomplished by two people at most, without lifting the child manually. The seat should also be able to be easily pushed around the classroom under full control.

11.1 Independent Seat Evaluation 1 - 1 day: Child A1, London, 11th November 2010

11.1.1 Evaluation objectives

The objective of this evaluation was to quickly check the design and geometry of the independent seat prior to a longer term evaluation. Time was allowed between this evaluation and the next for minor redesign and modification.

11.1.2 Preparation

The initial evaluation took place in the physiotherapy gym, in a quiet environment away from the child's classroom. The latter part of the evaluation was in A1's classroom. The seat was prepared for the child as much as possible prior to his arrival to minimise the time that he would be sitting in the seat while it was adjusted around him; and to minimise the number of times he would need to be put in and taken out of the seat. Previous experience has shown that when the children are relaxed and calm, they seem to have fewer less intense spasms.

Child A1 was not as anxious about evaluations as Child R1, so it was possible to conduct the evaluation without disrupting the remaining members of his class. He was measured in his classroom, and the measurements used to configure the seat in his absence.

Child A1 was brought into the gym by his teacher and was introduced to the research team. It was not clear whether he remembered them, but he seemed pleased to meet them. The research engineer explained to him what was to be done in simple language, maintaining hand contact with him to reassure him.

The child was seated in the chair and it was adjusted to fit him. Had his measurements not been taken beforehand, he would not have fitted in the chair.

11.1.3 Evaluation session

A1 sat symmetrically in the chair, and relaxed into it, exploring the movement that was possible. The backrest spring rate was doubled and the hip spring rate reduced to encourage movement of the legs in preference to movement of the back during hip extension. Curved lateral supports were applied just below the axilla, and the pelvic belt was tightened.

A1's hips were positioned slightly abducted. His thighs fitted snugly into the thigh trays, and were secured loosely with the thigh straps. His thighs did not lift out of the trays during use. His lower legs were loosely secured to the sides of the leg segments of the chairs, and his feet were secured firmly to the front of the foot board across the toes of his shoes. His heels were not secured.

It became clear that the proximal end of the inner lateral faces of the thigh trays were impinging on his inner thigh. He was protected from abrasion and pressure temporarily by an occupational therapist interposing her fingers between the child and the thigh tray. When it was clear that the seat was otherwise suitable for him, he was removed from the seat and the thigh tray corners were removed so that he could sit in it independently. He was placed back in the seat and sat in it comfortably.

After A1 was removed from the seat, he was checked for persistent red marks indicating pressure points on the skin. None were found except slight marking on the inner thigh where the thigh trays were modified. A1 was returned to his classroom and the research team left. The staff later asked A1 about the seat and he indicated that he liked it.

The evaluation session was video recorded for future reference, but no sensor data was collected.

11.1.4 Evaluation Outcomes

The primary objective of the evaluation, to assess the suitability of the seat for Child A1, was achieved. It was demonstrated that A1 could sit in the seat comfortably and independently whether experiencing a spasm or not. This had not been achieved for him before.

The loss of lumbar contact that had occurred with the semi-soft prototype was resolved with this seat, and A1 maintained good contact with the backrest during movement. However, the new pivot point resulted in his shoulders and head sliding up and down the backrest during movement. This created shear on the skin of his back, which is a risk factor militating against skin integrity.

A1 was observed to be relaxing into the seat, and experimented with voluntarily moving the leg supports in an alternating gait-like pattern. This voluntary movement had not been seen previously when he was in his static seat, as his lower body was immobilised.

The thigh trays were clashing with the weight bearing saddle (a bicycle saddle) during movement. They needed significant modification to prevent this clash while still providing sufficient abductive support to the occupant's thighs.

It was found that the thigh trays did not need to provide lateral support to the outer (lateral) faces of the thighs as there was constant abductive pressure on the inner (sagittal) faces of the thighs.

The foot supports with toe-only constraint and a sagittal plate did not provide sufficient positive alignment of the feet. It was necessary to redesign the foot supports with stronger springs and different constraints.

The head support integrated into the backrest provided insufficient support and needed to be replaced.

It was considered that a weak bungee cord should be used to provide a small return force on the knee joints. This was later abandoned.

The careful preparation and prior adjustment of the seat resulted in a calm and orderly evaluation with little distress caused to the child.

11.2 Independent Seat Evaluation - Comfort Checking: Child J1, Bath, 15th November 2010

11.2.1 Objective

The objective of this evaluation was to check the seat for comfort with a child able to speak and report in detail issues relating to comfort and feel.

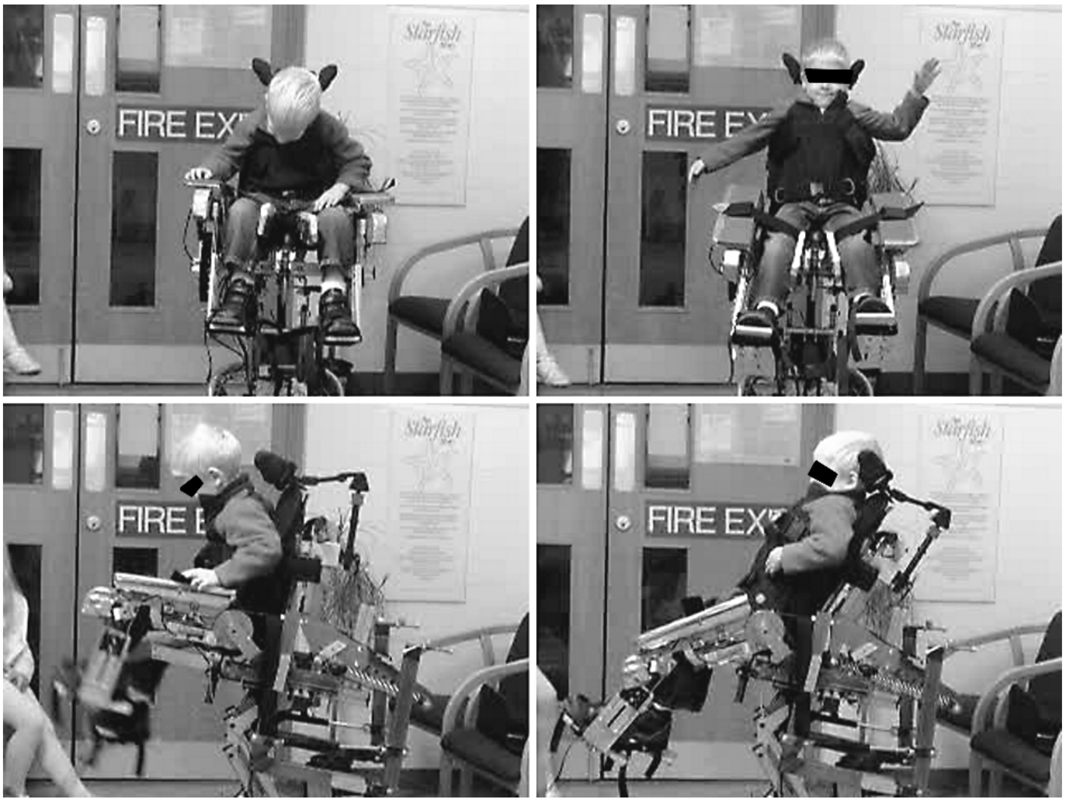

Figure 11-1: Four photographs of J1 taken from the video of the evaluation, showing him in voluntary extended and flexed positions in the seat.

11.2.2 Evaluation summary

This quick evaluation was with a child with ataxic cerebral palsy who was significantly less disabled, but the same size as the children in the study. He was able to speak and describe the feel of the seat. He confirmed that the seat was comfortable and he clearly enjoyed playing in it. The problem with longitudinal displacement of the backrest during backrest rotation was confirmed. As the backrest reclined, J1's head and back slid up the backrest. Though this did not cause him discomfort, as with A1's evaluation, it did cause the head support to become positioned too high. Photographs of the evaluation in progress are shown in Figure 11-1.

11.3 Independent Seat Evaluation 2 - 1 week: Child A1, London 24-11-2010

11.3.1 Evaluation objectives

The objective of this evaluation was to check the modifications made to the seat since the previous evaluation, identify any further changes required, and then to trial a longer term evaluation. The modifications made were:

1. A demountable tray was built which could be adjusted for height and position to suit A1.
2. The thigh trays were rebuilt to be wider so that they did not constrain his lateral thighs.

11.3.2 Session 1: 24th November 2010

This evaluation was split into two sessions as several problems were identified during the first day which needed to be rectified before the evaluation could proceed.

1. The proximal corners of the new thigh trays needed to be removed as they were causing pressure on A1's legs.
2. The direction of pull and buckle attachment on the thigh straps was reversed so that the slight axial moment they applied to the occupant's legs caused the hips to rotate outwards rather than inwards.
3. Due to A1's general low tone when not experiencing a spasm which prevented him from maintaining an upright posture, an 'H' body harness (a 4 point 'BodyPoint' harness) was used. It abducted A1's shoulders and helped him to maintain an upright head position.

In addition to these problems and their accompanying solutions, the following observations were made:

1. A1's spasms were asymmetric: he was pushing harder on his right side than his left.
2. His heel lift was asymmetric, with his right heel lifting more than the left.
3. A1 was successfully fed while sitting in the seat.
4. It was also noted that it took three people to put A1 in the seat. Transfers into and out of the seat were challenging, and it became clear that easing transfers should be a significant area for future design optimisation.

11.3.3 Session 2: 26th November to 1st December 2010

The evaluation was held in A1's classroom. When the evaluation team arrived, A1 was made aware of their presence and was pleased to see them.

He was placed into the chair and it was adjusted to fit him once again, with the seat joints being aligned as closely as possible to the child's anatomical joints in his hips and knees. The head support was added and positioned behind his head. Additional padding was placed between his inner thighs and the abductive plates of the thigh trays. The research team left the seat at the school, returning to collect the seat on the 1st of December.

11.3.4 Evaluation outcomes

This evaluation demonstrated that the seat was suitable for Child A1. He sat in it for prolonged periods of time of up to four hours. He was relaxed and functional, and had no observable adverse effects, including an absence of skin reddening from excessive pressure. His participated in classroom activities; for example his class teacher assisted him to join in a class activity planting plants in pots. With much help from his teacher, A1 put compost in a plant pot.

Observations from the video of the evaluation sessions included:

1. A1 made frequent small movements, many of which were voluntary. These included reciprocating 'cycling' movements of his legs. These movements were more frequent and more controlled at the end of the evaluation (1-12-2010) than at the beginning (26-11-2010).

2. Although A1's spasms occurred frequently, they did not appear to distress him, and seemed less intense than when in his usual static seat.

3. A1 used his hands on the tray to help to maintain an upright head position

4. A1 responded to music being played in the classroom, vocalising and smiling. His vision is poor, and he is more responsive to auditory stimuli than visual.

5. He was fed fluids and solids while sitting in the chair. See Figure 11-2.

11.4 Independent Seat Evaluation 3: Child R1, London, 17th December 2010

11.4.1 Objectives

There were two objectives for this evaluation:

1. To assess Child R1 for readmission to the project

2. To perform a short preliminary evaluation of the seat prior to its configuration for a week long evaluation at Child R1's school.

11.4.2 Preparation

The seat was set up in a clinic room at the hospital. Child R1 was brought to the room, but was not shown the seat. He was observed to be less responsive than he had been previously, and did not appear to recognise people there. While he was in the seat, he extended frequently (though less so than in previous evaluations), but was constrained by the seat straps and was unable to move substantially.

Child R1's key dimensions were measured before he was taken from the room to a nearby waiting area. These dimensions were used to configure the seat to fit Child R1. The abduction angle and the spring parameters were retained from Child A1. The video camera was positioned and the space around the seat was cleared.

R1 had grown since the previous evaluation in which he had participated over a year previously. His growth rate had increased due to his feeding improving after he had a gastric ‘button’ fitted for liquid feeding directly into his stomach.

11.4.3 Evaluation

Child R1 was brought into the clinic room and put immediately into the seat. The seat was the right size for him and did not need any further adjustment to fit him. He was responsive to voices, and occasionally smiled. A recurring pattern of an extensor spasm followed by a flexor spasm was observed to be occurring while he was in the seat, causing the legs to extend and the backrest to recline backwards. He was not distressed. He was observed sitting in the seat for eleven and a half minutes. It took four and a half minutes to position and secure him in the seat. A still from the video is shown in Figure 11-3.

R1 was secured in the seat with the lap strap, two lateral thoracic supports, the chest strap, the thigh straps and toe straps. The four point BodyPoint harness, used initially, was removed and substituted for a chest strap across the lateral supports as he was hanging on it and it rubbed against his neck.

R1’s background muscle tone was lower than when he was previously seen, and his head control was further impaired. He frequently turned to the right in an Asymmetric Tonic Neck Reflex (ATNR), and was not always able to keep his head upright. His flexor and extensor spasms were not so strong or as frequent as when he was previously seen. The time course of the evaluation is shown in Table 11.1:

Photographs from the evaluation shown in Figure 11-4.

11.4.4 Evaluation summary

This evaluation was conducted in a clinic at Great Ormond Street Hospital. During the summer of 2010 R1 acquired a serious cerebral infection which led to a prolonged seizure early one morning, after which his spasms stopped. His participation in the project was temporarily suspended pending any change in his condition, as he no longer met the inclusion criteria. In the autumn of 2010 his spasms returned and it was decided to reassess him after his physiotherapist reported that he was once again unplaceable. After the return of his spasms, his NHS seating team supplied a commercial JCM seat with a dynamic backrest and a contoured seat base cushion.

Child R1 attended an X-ray clinic and was then brought to the assessment room for the seat evaluation. The evaluation proceeded according to plan, and R1 sat in the BIME seat considerably more quietly than he had during previous evaluations, without becoming distressed. In this respect his presentation was different to previous seat evaluations, where he had been highly active and often distressed. His general muscle tone was lower, and his alertness and interactions with the research team seemed to be reduced compared with previous evaluation sessions. Also unlike previous evaluations he seemed to enjoy sitting in the seat, smiling on several occasions when sitting in the chair.

Due to heavy ongoing snow-fall, the evaluation was shortened and the clinical assessment planned after the seat evaluation was abandoned to allow R1 and his mother to travel home early.

Figure 11-2: An example of A1 engaging in an activity in his seat: A photograph of A1 feeding.

Table 11.1: A table of the timecourse of the evaluation of the seat by child R1 at Great Ormond Street Hospital on 17th December 2010.

Time (min:sec)	**Event**
00:19	R1 placed in the seat;
04:56	Toe strap adjustment completed - R1 secured and sitting, with a head down position (See Figure 11-4: LEFT);
05:19 - 06:22	Therapist and Engineer fitted a chest strap;
06:40 - 06:56	R1 independently raised his head to an upright position (without a head support) and looked at the camera being used to record the session;
07:03 - 07:20	R1's mother manually raised R1's head to an upright position, however this initiated a spasm and an ATNR. She released him and he returned to a head down position;
07:26 - 07:56	R1 independently raised his head to an upright position again, and maintained it from 07:29 while holding his mother's hands in front of him. During this time he was intermittently pushing on the leg supports at about 0.3Hz;
07:50 - 08:10	Engineer and Therapist removed the 'H' harness;
08:11 - 08:22	R1 again independently raised his head to an upright position and maintained it from 08:14 to 08:22. He continued to hold his mother's hands in front of him (See Figure 11-4: CENTRE);
08:23 - 08:37	R1 again independently raised his head to an upright position and maintained it from 08:26 to 08:37. He continued to hold his mother's hands in front of him;
09:26 - 10:37	Engineer raised R1's head to an upright forward facing position. R1 sat upright, looking at the camera, with head support from the engineer's hand and forearm. R1's mother commented that R1 liked head support to be very consistent and that if it changed then he would 'push against it' until he got used to it again. (See Figure 11-4: RIGHT);
11:34	R1 was removed from the seat.

Figure 11-3: A still from the video of R1 in the seat during the evaluation on the 17-12-2010 at Great Ormond Street clearly showing the seat mechanism and his seated position. He is hanging forwards on his straps in this photograph, so the four point BodyPoint harness was replaced with a broad chest strap for subsequent evaluations.

Figure 11-4: Three photographs of R1 evaluating the seat at Great Ormond Street Hospital in December 2010. The photographs show: LEFT: Securing R1 in the seat; CENTRE: R1 with an independent upright head position. RIGHT: R1 with a supported upright head position.

11.4.5 Conclusions

R1 had changed significantly since his previous evaluation of a seat: his spasms were much reduced, both in intensity and frequency. He sat calmly and seemed to enjoy his time in the seat, exploring the movement.

R1 showed a considerable improvement in head control during this evaluation after the adjustment and securement was complete; independently maintaining an upright head position without a head support for short periods of time.

It was not known how much of the head control improvement was due to the seat, and how much was due to neurological change as a result of his seizure. During the evaluation, his mother referred to his usual seating and commented that:

> *"With this headrest that we've got, he always has trouble with the headrest. If the headrest moves he's uncomfortable; he has to be in a certain position and stay like it. If it moves slightly, he's not happy in that chair. He then pushes on it, pushes it, and gets his head stuck to the side where he pushes back against it."*

Head position was very important for R1. During this evaluation, head support was intermittently provided by the project engineer and R1's mother, with several different strategies being briefly explored, including anterior and lateral support, occipital, and sub occipital support. Photographs of three of these strategies are shown in Figure 11-5.

Conclusions from the evaluation that required modification of the seat prior to the next evaluation were:

1. A sub occipital or occipital head support needed to be added. This was not fully explored during the evaluation as there was not sufficient time due to the weather. The head support needed to prevent R1 moving his head outside its area of support, as had been occurring with his usual seating.

2. A broad chest strap was needed to prevent him 'strap-hanging', instead of either the four point harness or narrow chest strap used during this evaluation.

Figure 11-5: A photograph of R1 in his seat during the December 2010 Great Ormond Street evaluation. This picture shows three of the head support strategies employed during the evaluation, and an example of R1 independently supporting his head.

3. The lateral thoracic supports needed to be raised by three inches to a subaxillary position (See the research therapist indicating the adjustment needed in the Top Right photograph of Figure 11-5).

11.5 Evaluation 4, Independent Seat: Child R1, Special School - Essex 11-1-2011

11.5.1 Objectives

To assess Child R1's response to the fully independent seat prototype for a week in his usual classroom context and to inform the design of the next prototype seat.

11.5.2 Preparation

Preparation for this evaluation was made in the physiotherapy room at R1's school. The seat was adjusted to his previously measured dimensions from the December 2010 session. The multisensory room was not available, so initially, the physiotherapy room was used. It was planned that further sessions beyond the initial one would be held in his classroom.

11.5.3 Evaluation - 10/1/2011

The primary aim of the first day of the evaluation was to determine how the seat should be configured for R1 for the remainder of the week. R1 was brought into the physiotherapy room and sat in the seat. The evaluation lasted fifteen minutes. It became clear very quickly that R1's response to the seat on this day was very different to his response when the seat was evaluated at Great Ormond Street Hospital in December 2010 (See Section 11.4). His movements and emotional state were much more like those from before his seizure.

Handling and transfers: Placing R1 in the seat was difficult and required three people. One lifted him, and two others secured him in the seat. He extended as soon as he sat in the seat and continued to have extensor and flexor spasms until he was removed from it.

Comfort: R1 appeared distressed in the seat, with intermittent crying. He was working very hard and became hot and sweaty. The proximal medial edge of the left thigh gutter was impinging on the saddle and needed adjusting. R1 was pulling his feet out of the foot straps. On removal from the seat, R1's Anterior Superior Iliac Spines (ASISs) were reddened. This was thought to be caused by the pelvic strap, which he was pushing against when extending and levering against the leading edge of the weight bearing saddle.

Movement: R1's movements were asymmetric: his left leg was flexing and extending with his spasms; while his right leg adopted a more static extended plantar flexed position, with increased tone for longer periods. His head was rotated towards the left (this was thought by the research OT to be because the engineer was standing on his left side). His arms were dystonic and athetoid. R1's therapist explained that he liked to have his hands held for stability and that in his current seat he had a pommel handle to hold on to.

After the evaluation: R1 was tired and needed time to calm down. He was gently laid on a mat on the floor and placed in a supine position. He adopted a preferred position which is shown in Figure 11-6. He lay on the mat in this position for a few minutes, with very little movement. The staff and research team discussed the evaluation and noted his extended head position (about 40° extended), which was similar to that adopted when he was sat on his mother's knee. His teacher described his postural strategy for maintaining eye contact saying *"if he makes eye-contact with someone, he brings his head right forward to that position, to make eye-contact"*. During this time on the mat his teacher gently rubbed his back.

At the end of the evaluation, the research team visited an upholstery shop and obtained additional padding for the pelvic strap and the saddle.

11.5.4 Evaluation - 11/1/2011

During the second day of the evaluation, the seat was moved from the therapy room to a large activity room. This was the only room available in the school at the time, and it was not ideal. The room was large, well lit, and had an echoey acoustic due to its hard floor and walls. It had none of the feeling of intimacy and security that was desired for evaluation work. In an effort to improve the environment of the evaluation, some screens were moved to create a smaller space, and a video player and television were set up to play films that R1 would enjoy. R1 was less distressed than during the previous day's evaluation, though he was still experiencing spasms at about 0.5Hz (10 spasms counted during 21s). See Figure 11-7.

Initial modifications: Additional padding was placed underneath the pelvic strap and between R1's legs and the abduction supports on the thigh gutters.

Evaluation: R1 evaluated the seat in three sessions of twenty two minutes, eleven minutes and sixteen minutes. Key observations are described below:

1. A head support was transferred from R1's usual seat and positioned similarly. R1 was able to maintain an upright head position with this support.
2. R1 was experiencing spasms at 0.5Hz while he was being secured into the seat, but was less distressed than the previous day, and was also less vocal. He was not crying.
3. He became more distressed when his feet were secured in the seat, and particularly when the chest strap was fastened. The chest strap was later removed.
4. R1 experienced gross motor dystonia in his upper limbs. When his hands were held by the research OT, his distress lessened.

Figure 11-6: A video still of R1 on a mat after the first evaluation session. He lay on the mat in this position for a few minutes, with very little movement. The staff and research team discussed the evaluation and noted his extended head position (about 40° extended), which was similar to that adopted when he was sat on his mother's knee. His teacher described his postural strategy for maintaining eye contact saying *"if he makes eye-contact with someone, he brings his head right forward to that position, to make eye-contact"*. During this time on the mat his teacher gently rubbed his back.

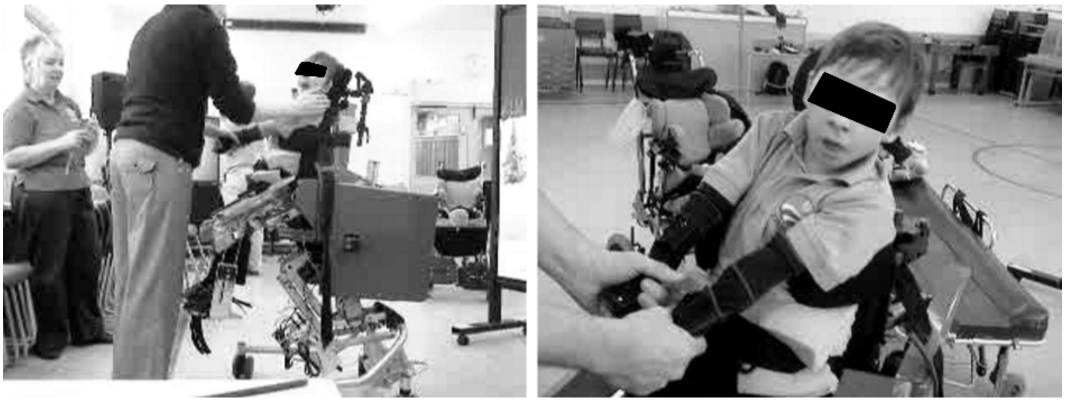

Figure 11-7: Video stills of R1 from Session 1 on 11-1-2011. LEFT: Sitting in the first independent seat while not moving after being asked to sit still for a photograph by his physiotherapist. RIGHT: Watching a Disney sing-along video on television during the evaluation. He has an engaged and functional head position.

5. For the most of the evaluation, R1 experienced spasms at about 0.5Hz. At 12m 52s into the video his physiotherapist asked him to sit still for a photograph, and he did so in an extended position for eight seconds, before resuming his movements after the photograph had been taken. This strongly suggests a) he has some degree of control over his spasms; b) that many of the movements that have been identified as spasms are voluntary; or c) the request to sit still initiated a prolonged spasm.
6. Seventeen minutes into the evaluation R1 was moved in front of the video player and TV. By the end of the evaluation, he was tired, but was only occasionally vocalising. His movement rate had decreased to 0.3Hz (measured over 1 minute), with pauses between groups of movements. Some of these movements were groups of alternating left and right leg movements, rather than whole body movements. These may have been voluntary.
7. R1's adductor spasm was strong enough to reduce the hip abduction angle of the left leg support.
8. There were no ASIS red skin marks on examination after his removal from the seat, and a slight reddening on his left inner thigh.
9. During the final session of the day, R1 sat quietly without appearing to be distressed. The session was used to test some hand carved foam pads used to protect his ASISs.

This session, several new issues were identified:

1. R1 was not sufficiently supported at his lower back in the sacral area. This was because the backrest was too high above the saddle. This also meant that the head support could not be positioned correctly as the top of the seat back was too high. This problem was solved by moving the backrest down to the lowest position on its frame. This required the backrest to be removed and new mounting holes to be drilled.
2. With the new backrest position, the lateral supports could not be positioned high enough, and R1 tended to slump sideways. The chest strap, which was attached to the lateral supports, was also too low and did not prevent him from hanging forwards. Both of these problems was solved by raising the frame that supported the backrest and the lateral supports.
3. With the head support in its new position, the backrest did not recline sufficiently during a spasm, because it fouled the top of the back-support mounting pillar. The top of the pillar (a 40mm x 40mm aluminium extrusion) was shortened so that sufficient movement was possible.

11.5.5 Evaluation - 12/1/2011

The evaluation at R1's school continued. The seat was not yet working well enough for a long classroom evaluation to be conducted, so iterative short evaluations, adjustment and modifications continued. It was noted on this day that R1 still had some residual noise on his chest when breathing. His mother considered him fit enough to attend school, but explained that she would take him to the doctor if it did not improve. R1 was tired, and had a relaxed morning. He evaluated the seat during two ten minute sessions in the afternoon. The research engineer was not present on this day.

Figure 11-8: This is a still from the video of the first evaluation session on 12th January 2011. R1 was very floppy on this day, and was not nearly so active as he had been on the previous day.

Evaluation: These two short sessions were conducted in the large activity room as on the previous day. R1 sat in the seat and watched a Disney sing-along video on the television. He was very floppy on this day, sitting very flexed while being secured in the seat - See Figure 11-8. Key observations are given below:

1. In sharp contrast to the previous day, R1 was very floppy during these evaluations. Before he was transferred from his usual seat he was sitting in a very flexed position, hunched over his pommel. He was not experiencing spasms. He was secured in the dynamic seat quickly, and continued to sit in the flexed position until the broad chest strap was secured. Additional truncal support was needed, compared with the previous day.

2. R1's pelvis was axially rotating right with his left hip moving anteriorly, causing pressure on his left medial thigh. It was also thought that his pelvis may have been tilting posteriorly. This was thought to be because of his asymmetric left dominated hip extension spasms and the effect earlier described where he was levering his pelvis forwards on the front edge of the weight bearing saddle.

   At the end of the day, R1's mother explained that R1 tends to sit symmetrically in his usual (rigid) seat. She felt that he had stronger spasms on his left side and noted that when in a standing frame his pelvis also axially rotates to the right.

3. R1 was extending at a rate of about 0.3Hz (18 extensions during 1 minute from 05:00 in session 1) and a similar rate in session 2. His spasms were less intense than the previous day, with less powerful extensions (reduced extension angle) and less active flexion following the extensions.

4. R1's head control was not good during this evaluation. He was frequently unable to maintain his head on the head support as he had the previous day. The research OT provided direct head support to R1 for much of the evaluation.

5. Two people were able to place R1 in the seat without difficulty.

No modifications were made on this day.

11.5.6 Evaluation - 13/1/2011

During this day, R1 evaluated the seat for two short sessions ((7 minutes and 10 minutes) with adjustments between, followed by a longer session of twenty five minutes. He was less tired than on Day 3, and did some good eye-pointing work in the morning.

Modifications and adjustments: Several changes were made to the seat during the day, before the long evaluation at the end of the day.

1. The backrest frame was moved so that the lateral supports could be moved higher.

2. The leg supports were moved forwards again to reduce the effect of the front of the weigh bearing saddle.

3. The hip extension spring rate was doubled to stiffen the leg movement and increase the feeling of security. R1 was still able to move the leg supports during spasms.

4. The pelvic strap attachment point was moved forwards to reduce the posterior tilting moment it applied to the pelvis.

Evaluation: These evaluations were carried out in R1's classroom, rather than in the activity room as before. The research engineer was present, and made the adjustments to the seat. Key observations are described below:

1. For much of the third session, R1 sat flexed, relaxed and calm in the seat without spasms while his hands were held in front of him by his class teacher. Prior to her touch, he had been experiencing spasms at about 0.3Hz. His seat was adjusted with about ten degrees of posterior tilt in space. He began to slowly extend at 0.35Hz while trying to raise his head to the head support, and then relaxed again in a flexed position for a short time before the extensions began yet again, though gently. Eventually he achieved a head up sitting position in the seat. Once this position was achieved, he began to extend gently at about 0.3Hz.

   The seat was raised from its tilted position to an almost upright position. R1 continued to sit with his head upright, looking at his teacher and extending gently at 0.3Hz. When the seat was

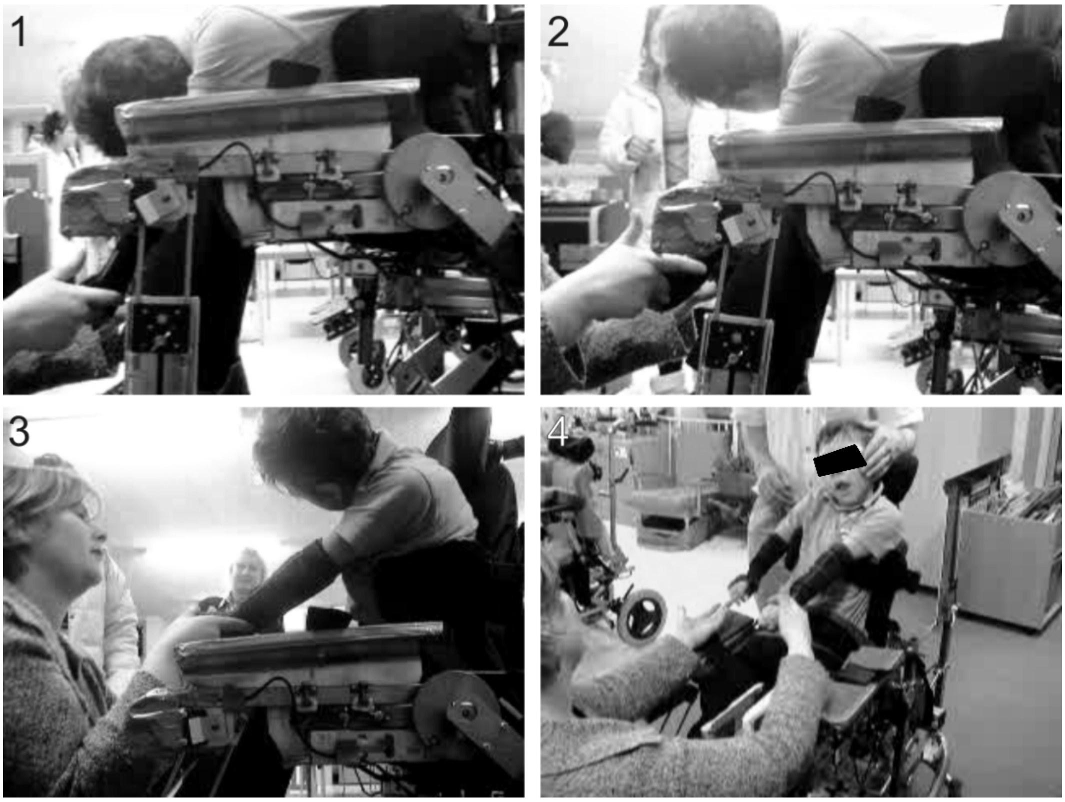

Figure 11-9: A series of stills of R1 achieving a head-up position in the seat during Day 4 of the evaluation in January 2010. This took him thirty seconds to achieve.

tilted close to upright, R1 once again sat flexed and head down, however he regained his head up position and was able to maintain it with a little additional lateral head support. This took him thirty seconds to achieve. A series of photographs from this session is shown in Figure 11-9.

2. R1 was quieter and less distressed than in previous evaluations. He sat relaxed and did not make distressed vocalisations, though he did make what his teacher described as ‘whingy noises’.
3. R1 became slightly distressed when the thigh straps were secured during the first session.
4. During the second session, R1’s teacher held a switch in a position where she thought he may be able to operate it, however he was not able to position his arm so that he could do so due to his dystonic movements.
5. With practice, one person placed R1 in his seat; and one held him while another secured the lap-strap.

11.5.7 Evaluation - 14/1/2011

The final day of the evaluation was held in R1’s classroom. He was sat in the seat by his teacher. He was experiencing frequent spasms, due to his emotional state at the time. As he was moderately distressed, his teacher talked to him about sitting in the seat, and asked him about each part of his body and limbs in turn to ascertain where he was uncomfortable. She had been teaching him to use two different signs for "yes" and "no" which were a blink and a slight shake of his head respectively. This methodical process yielded the information that he was uncomfortable on his pelvis due to the pelvic strap on the seat. This strap was adjusted to make him more comfortable.

He was taken to a table and spent some time working at the table, while a side view of the seat was video recorded. At this time, the research team concentrated on his spasm movements and did not record movement of his hands and head.

After about five minutes at the table, he was taken outside with the rest of his class who were "going on a lion hunt". The teacher recited the popular children's book from memory as they walked or rode in their seats to the playground and the around some of the playground furniture.

R1 seemed to enjoy this time and was included in the game by his teacher. He seemed to be sitting comfortably. On returning to the classroom it was time for him to go home, and after forty minutes in the seat he was removed from it. On inspection of his skin by the school staff, some redness on his skin around the pelvic strap was observed which was likely to have been caused by the pressure he exerted on the strap while levering himself forwards on the edge of the saddle while extending. This is in contrast to the previous day when he was more relaxed with the same seat configuration.

11.5.8 Evaluation summary

This evaluation tool place at R1's school in Essex. Following the successful evaluation at Great Ormond Street in December 2010 and the observed changes in R1, it was intended that this evaluation would assess his use of the seat during a week at school, after a day of setting up time at the beginning of the week. Setting up the seat for R1 proved to be more challenging than was anticipated, and took up the entire week of the evaluation, as R1 had changed yet again. It was not known why his condition was changing, but possible reasons included on-going changes resulting from his seizure during the summer, and a severe chest infection that he acquired over Christmas between the two evaluations (for which he was hospitalized). It became clear very quickly that R1's condition was much more like his condition before his seizure, with frequent whole body extensor spasms. The environment in which he was evaluated, though not ideal, was the best that could be achieved in his school at the time, given the constraints on the availability of teaching spaces.

Seating him proved challenging. This evaluation was only moderately successful, with progress being made towards successful seating, but no ideal solution being found. The seat was modified from its original configuration, with changes being made to the backrest support and the leg supports. A still from the video of R1 in his seat is shown in Figure 11-10. On the last day of the evaluation, R1 used his seat to go outside 'on a bear hunt' with the rest of his class. He enjoyed this outing and sat well.

11.5.9 Conclusions

This evaluation was key to the design of the seat. It was a significant contrast to the previous evaluation with A1 in London. R1 was a far more complex child, and placed greater demands on the seat design. Days one to three were used to determine the dimensions and basic configuration for the seat, while

Figure 11-10: A photograph of R1 in the independent seat during the January 2011 evaluation at his school in Essex. The people present, from left to right are: a school occupational therapist, the research occupational therapist, (his class teacher, obscured), his school physiotherapist, R1, and the research engineer. The evaluation is taking place in a large school activity room that the staff made available to the research team for the week, except when it was needed for indoor sports activities. This photograph is a still from a video recording.

working with a child who was uncertain about the seat and consequently more reactive to spasm stimuli. Nevertheless, the seat was configured, and the sessions at the end of day three and day four showed that R1 was able to calmly sit in the seat.

The day 4 sessions were carried out in R1's classroom with his teacher present, without noise, and with a distracting video playing. He teacher was skilled in understanding his communications and in handling him; for example when tilting the seat, she knew how far to go without initiating spasms. She also engaged him with activities. The result of the improved environment and the presence of R1's teacher significantly improved his emotional state during these sessions. He was much calmer, and his spasms were less intense that during previous evaluations when he was breathing rapidly, working hard, and becoming hot.

The day five sessions again showed the impact of R1's emotional state on the seat evaluation, but also that the seat could be used during table top activities.

With this in mind, the following conclusions were drawn about the design of the seat for R1, and about R1 himself:

R1's spasms and sitting

1. R1's spasms and extensor movements were highly dependent upon his emotional state in their intensity, but their frequency remained within a broadly consistent range of 0.3Hz to 0.5Hz.
2. R1 was sensitive to how his head was supported. If it was incorrectly supported, he would become distressed and experience more intense spasms (as reported by his mother in December 2010).
3. R1's spasms and movements were asymmetric, with his left side being stronger and more active than the right. This asymmetry led to pelvic rotation when he levered his thighs on the leading edge of the weight bearing saddle.
4. R1's rest state could vary between being very floppy and needing substantial postural support, to being active and needing little postural support.
5. R1's head control was highly variable, ranging between being able to achieve independent head control and requiring total head support for sitting and social engagement.
6. R1 had some voluntary control of his spasms, being able to at least suppress his spasm intensity and possibly, on occasions, inhibit them completely.
7. R1's adductor spasm was powerful, and required a strong structure to resist it while achieving the desired angle of abduction of his hips.

Seat geometry

1. The seat hip pivots should remain coaxial with the child's hip joints.
2. The backrest pivot should not be behind the child's back, and should be coaxial with the child's hip joint (as in the semi-soft prototype). This is to reduce shear between the child's back and the backrest, and also to maintain the head support position.

3. The leading edge of the weight bearing saddle should be sufficiently far back that the child cannot lever his pelvis forwards upon it.

4. A variety of head supports should be available, and they should prevent an active child from moving his head from outside their supporting area.

5. Lateral support positions should be sufficiently adjustable to enable them to support the child immediately below the axilla.

6. A range of thoracic constraints should be available, including a four-point harness and a broad chest strap.

7. The spring strength should be variable through a wide range, but is not critical. Thus it could be achieved though the choice of certain springs from a range of springs with various fixed spring rates, rather than an infinitely adjustable mechanism.

8. The pelvic strap should be broad, and should be anchored close to the hips of the child so that it does not apply a large posterior tilt moment to the pelvis. Four point anchoring would prevent the strap from riding up over the child's Anterior Superior Iliac Spines (ASISs) during movement in the seat.

Seat fittings

1. The seat should be fitted with a grab bar or tray to enable a child's arms to be stabilised.

2. The seat should be fitted with a tray to enable activities to be maintained in a good position, and also to provide support for the child.

3. The seat should be fitted with a push handle to enable it to be easily moved around the classroom.

4. Transfers of a child into and out of the seat should be considered in the design.

5. A new foot support constraint system needs to be designed that allows the heel to lift but does not allow the foot to be removed from the foot plate.

Chapter 12

Dynamic Head Support

Part of the overall plan for the whole body dynamic seat is to incorporate a dynamic head support support. There was insufficient time and resources within the funded research project to achieve this, so in parallel with the dynamic seating research, the author initiated and supervised an undergraduate student project in the Department of Mechanical Engineering at the University of Bath. Under the guidance of the author, the student, Richard Sheppard, investigated the movement paths of the head and designed a dynamic head support that followed anatomical paths in its movement. The student measured the head movement paths of a healthy volunteer using a three dimensional motion capture system called CODA[55] which uses infrared cameras to detect the position and orientation of small active tags that emit infrared light. The point clouds from the CODA system were imported into CAD software for analysis and conversion into three dimensional paths.

12.1 The need for a head support

While a dynamic seat (such as those described in this research) provides accommodation of movement from hip and spinal extension patterns, extension and rotation of the head and neck are not accommodated. The study aimed to design, prototype and evaluate a dynamic head support that could be used with the compliant seat, and also independently with other seating systems and wheelchairs. In particular the support was designed to match the anatomical movement path of the head, reducing shear forces and abrasion on the scalp. Many disabled people using head supports find that their hair becomes matted and abraded, and their scalp can become sore where their heads bear against their supports. See Figure 12-1 for a diagram comparing static and dynamic head supports.

A literature review of current dynamic head support designs yielded only a few simple head supports ([56, 57] for example). Most research into this field has been into the design of dynamic head supports as car head restraints([58] for example). Importantly, the literature review failed to yield any quantitative data on the anatomical head *path* during extension and lateral deviation. Whilst there were many papers and books describing the range of movement of the head, there were no papers found that described the path of the head's movement *during* extension and lateral deviation. It is unlikely that this research has not been carried out, however it was not found as a result of a thorough search.

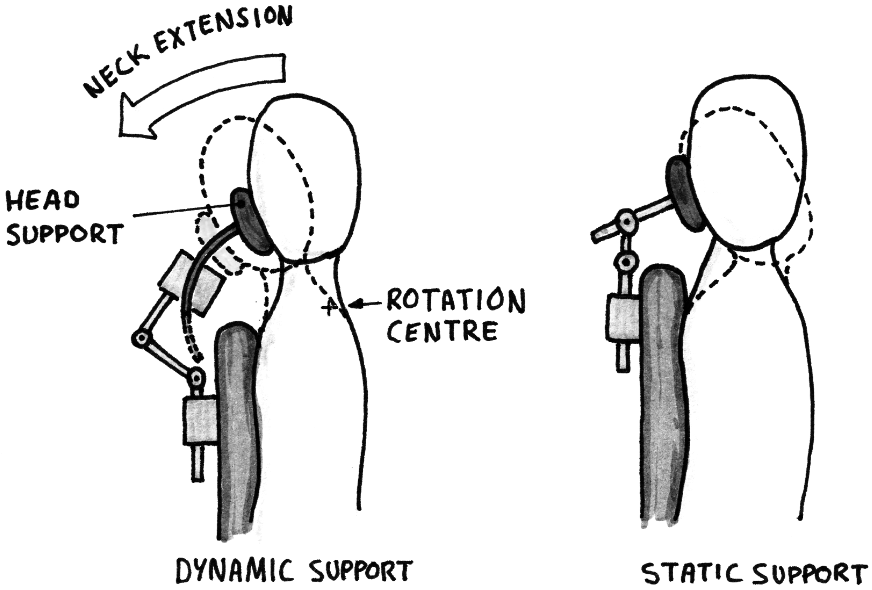

Figure 12-1: A diagram comparing a dynamic head support *(LEFT)* and a conventional rigid head support *(RIGHT)*. The dynamic head support shown allows posterior extension of the neck about an anatomical axis.

This lack of reported studies of head biomechanics was rectified with a simple motion study carried out by an undergraduate student in the biomechanics laboratory. Using the CODA system, a healthy volunteer was measured moving his head through a planned series of movements that described the range of movement of his head, and enabled capture of the motion path of his head in three dimensions.

12.2 Measuring normal head movement paths

The motion path of a healthy volunteer's head during flexion, extension, rotation and lateral deviation was captured in the biomechanics laboratory using the CODA motion capture system. This system uses infrared cameras to capture the movement of active infrared nodes that are attached to the object that is to be tracked. The system records a series of three dimensional spatial coordinates for each node, relative to a base node that is placed on a fixed point. A motion path can be reconstructed from this point cloud by linking successive nodal positions. If a three dimensional model of the object being tracked is mapped on to the nodal positions, then the position and orientation of the object can be captured as it moves through the measurable space.

12.2.1 Method

In this study a volunteer was sat on an upright seat in the middle of the laboratory and infrared beacons were attached to his head and shoulders in key positions – see Figure 12-2. Two motion system sensors (containing multiple infrared cameras) were positioned so that the head nodes were in view of both

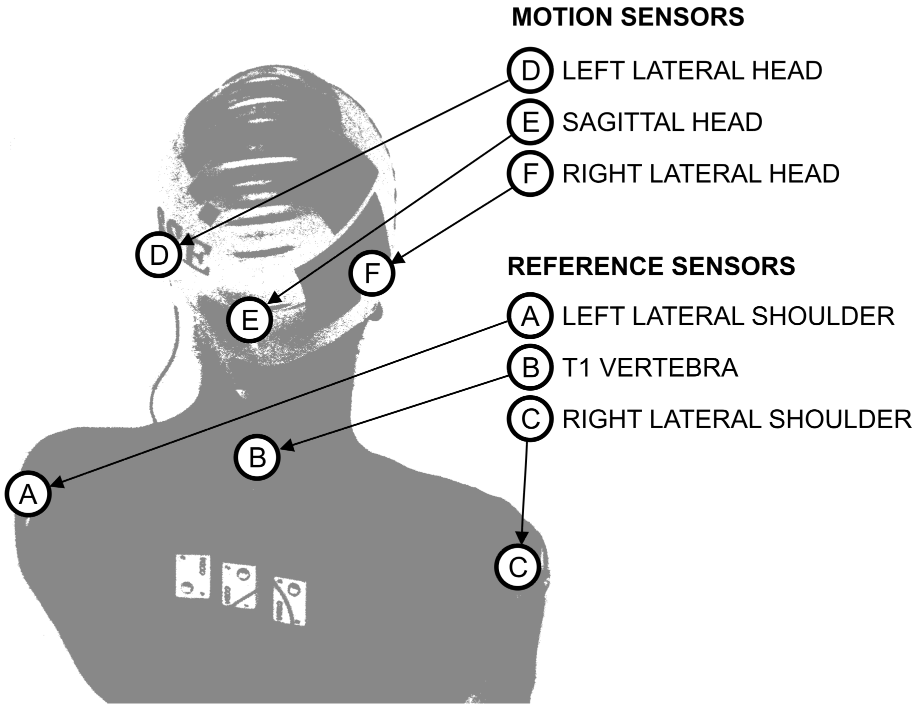

Figure 12-2: A diagram of the positioning of the motion capture system nodes on the healthy volunteer's head.

sensors most of the time, and at least one sensor all of the time. A single sensor unit is capable of determining the position of a node in view. If a node is in the view of more than one sensor, then its position can be determined more accurately.

The volunteer was asked to move his head through a series of single plane flexions, extensions, lateral deviations and rotations that would describe the motion path of the head. He was also asked to simulate the kind of multiaxial and multiplanar motion that might occur during an extensor spasm. Such a simulation is *not* the same as a real extensor spasm, but it's motion is thought to be approximately correct. See Figure 12-3

12.2.2 Results

The data were analysed by creating three dimensional point cloud plots that were imported into MATLAB where they were plotted. Once plotted, the data was inspected and arcs were fitted.

Despite the complexity of the head and neck musculo-skeletal anatomy, the sagittal motion data described a simple rotation about a fixed axis normal to the sagittal plane that passed approximately through a point just posterior to the inferior larynx. See Figures 12-4 and 12-5.

Lateral movement of the head was also approximately through an arc, though not as clearly so as in flexion/extension. It is sufficiently close to an arc that a simple radial mechanism could be used for a dynamic headrest accommodating this movement. See Figure 12-6.

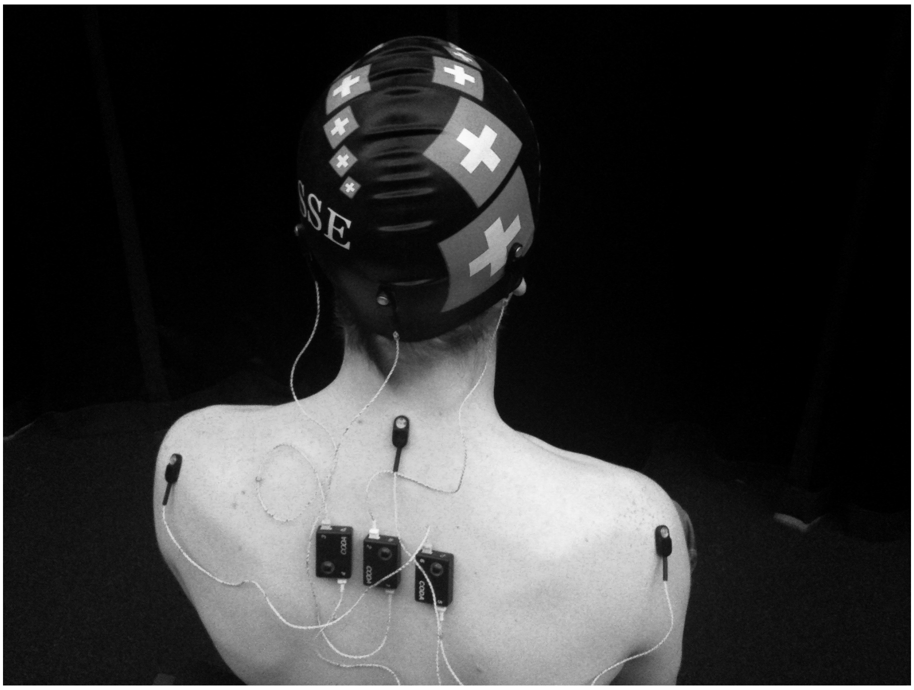

Figure 12-3: A photograph of the healthy volunteer during measurement of his head movement path using the CODA motion capture system. Three sensor nodes can be clearly seen on the participant's back, and three less clearly on his head.

12.3 Evaluation of a soft prototype by a potential dynamic head support user

The author and the project research occupational therapist visited a long-term client of the therapist to observe his use of a head support, and to assess the impact of a dynamic head support using soft prototyping methods. The therapist and engineer visited the client in his home, and assessed him in his bedroom. He lives in shared, supported and adapted accommodation.

The client (we shall call him Daniel) was a young adult with cerebral palsy and extensor spasms. When he was younger, he exhibited severe and frequent spasms, but over time his range of motion has decreased and he became much stiffer and less able to move. His spasms were not as powerful as they were when he was younger. His posture was asymmetric, with a strong tendency to turn to the right. His legs were windswept and one of his hips had subluxed and dislocated. He could not speak and controlled an electronic communication aid by moving a self-adhesive spot placed on his forehead just above his eye-line. The communication aid has sensors that tracked the movement of the sticker in two dimensions, and highlighted different symbols on a two dimensional array on the aid as he moved. He paused his movement and holds his position, highlighting a particular symbol to add it to the sentence he was constructing. In this way he was able to construct meaningful sentences from a reasonable vocabulary. Although sentence construction was slow, it was a substantial advantage for him to be able to 'speak' in this way, when compared with attempting signs by hand or difficult-to-understand

Lateral Graph of Sagittal Head Flexion/Extension

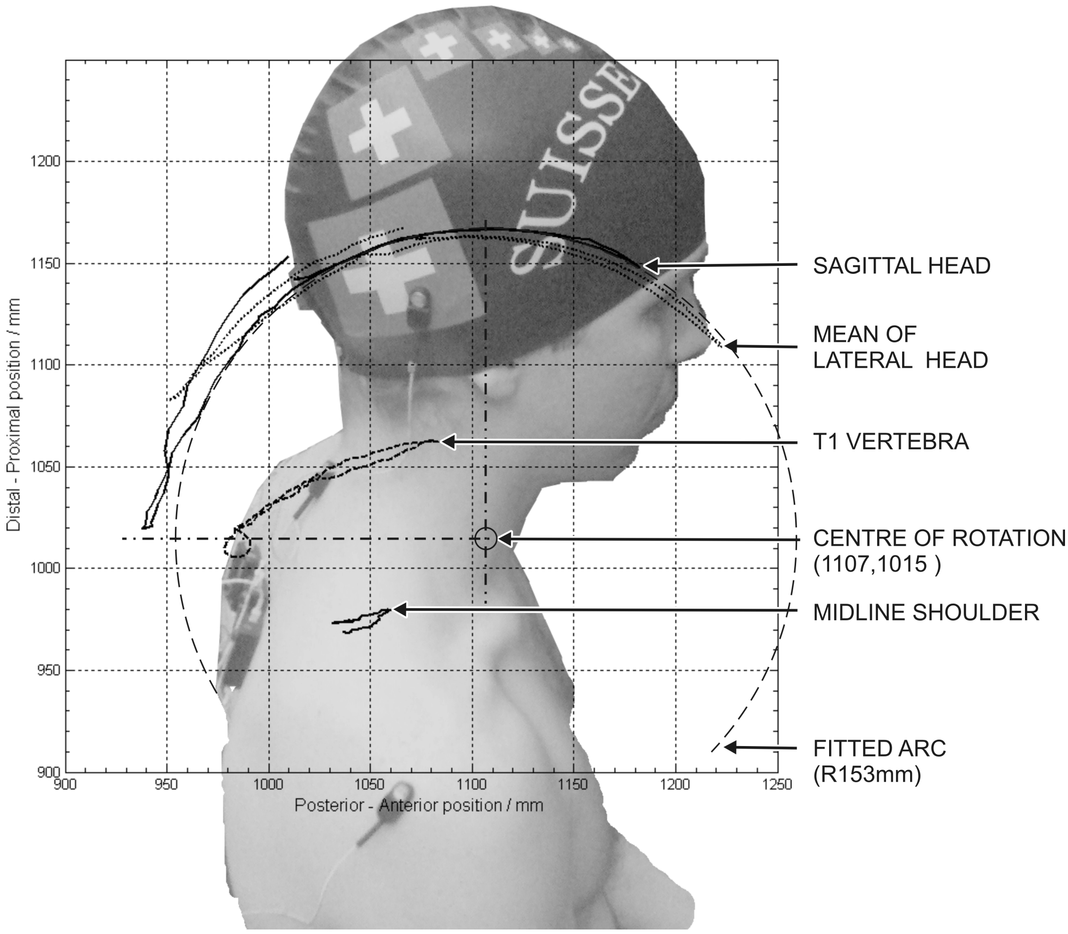

Figure 12-4: A plot of the flexion / extension motion paths overlaid on a photograph of the volunteer. The paths represent the motion on the volunteer's head in the sagittal plane. The fitted arc used to determine the centre of rotation is also shown.

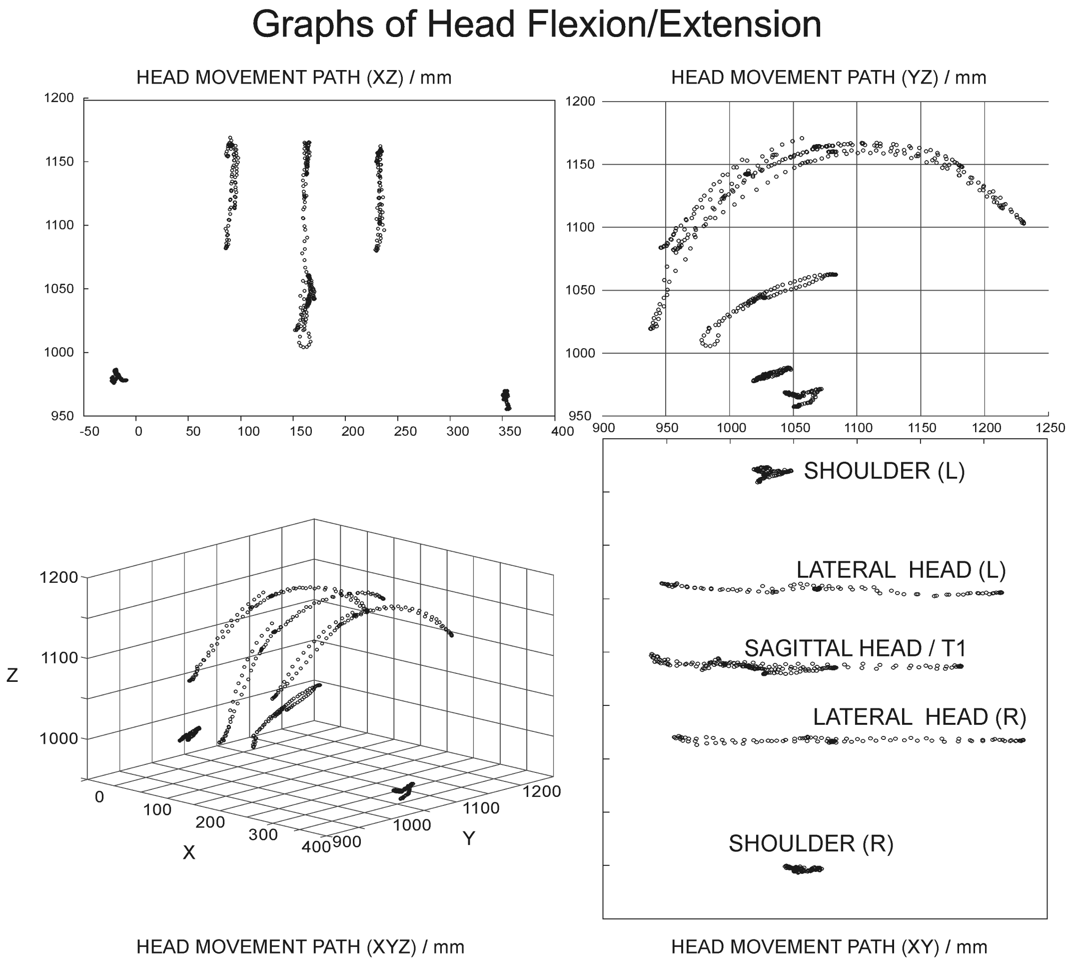

Figure 12-5: Plots of the head flexion / extension data in four views, showing the clear circular movement path of the head in this plane.

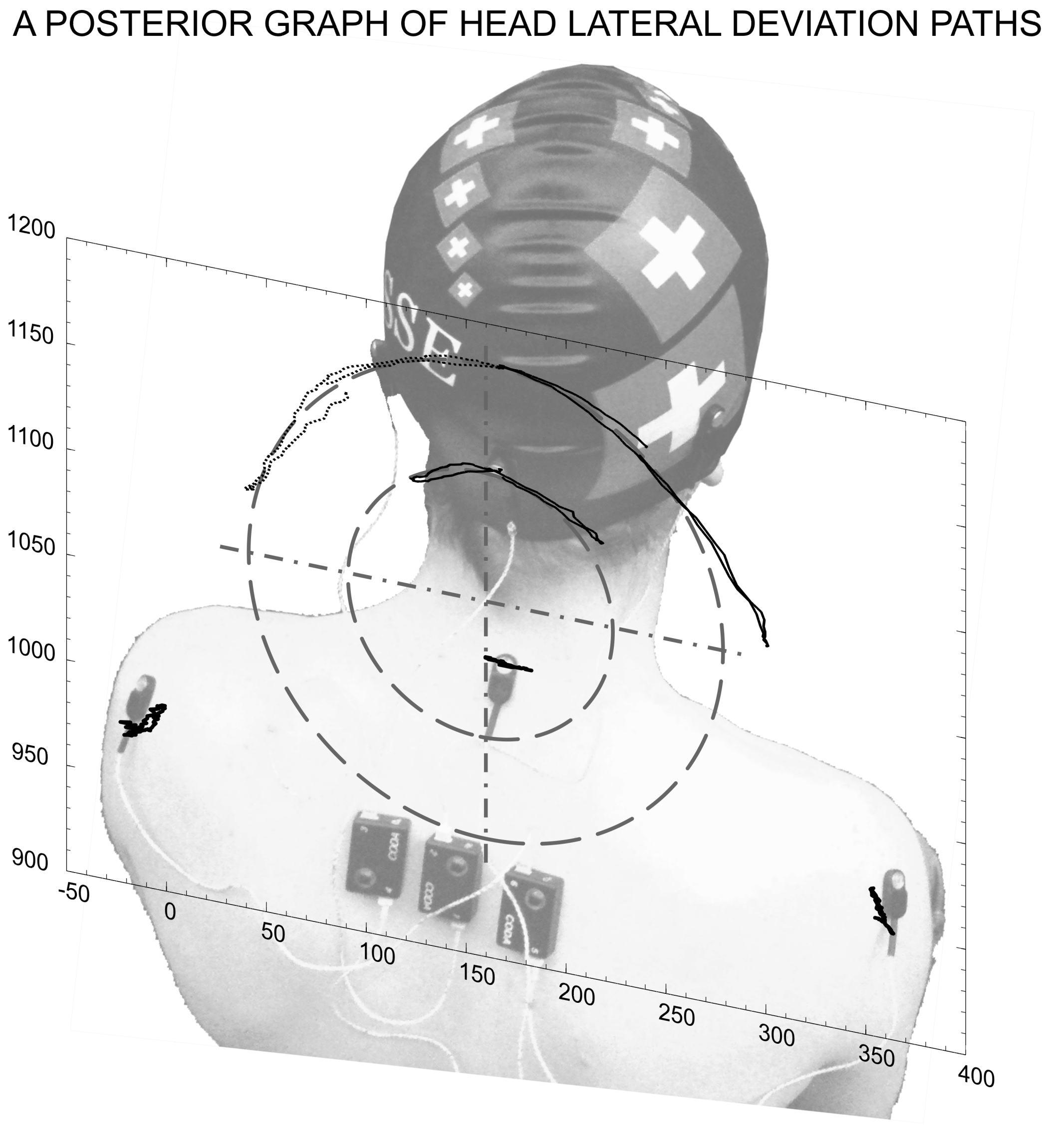

Figure 12-6: A plot of head lateral deviation data. A fit of the data to a circular path is plausible but not so clear in this case. A larger data set is needed.

Figure 12-7: A series of three photographs showing Daniel's head extensor pattern. He no longer extended his whole body. He used his head to operate a communication aid. This dramatically improved his ability to communicate as he was otherwise non-verbal.

vocalisations.

A dynamic head support was simulated, providing simple sprung support and allowing movement in axial rotation, flexion/extension and lateral deviation. The research team talked to Daniel, and, using his communication aid he was able to provide useful comment on how a head support should be designed. This short evaluation yielded the following information:

1. A dynamic head support would have been useful for Daniel because it would have been more comfortable, and aided his use of his communication aid. It also reduced the shear between the support and his head by accommodating his movements. Using his communication aid, Daniel explained that it would be useful if the head support moved. However the range of movement he needed during normal use was small.

2. He needed a variable contact position on the head support, depending on his activity.

3. The spring rate, preload and home position of the seat support needed to be adjustable.

4. The support needed to have two modes - one for normal non-spasmodic use in which it was able to move small amounts with very little resistance; and a second mode for use during spasms where a larger range of motion was possible and the applied forces were much higher. This requires either an intelligent active-dynamic support or a two stage passive-dynamic mechanical system.

5. He did not need a dynamic foot support, and stopped pushing on his footrest when he was nine.

6. He enjoyed the 'dynamic headrest' simulated by the research engineer.

7. He explained that using the dynamic support did not affect how he felt elsewhere in his body.

12.4 Discussion

This short study has yielded several important findings. Following a negative search for data on head movement paths, Flexion/Extension and Lateral Deviation of the head were measured as circular rota-

Figure 12-8: A series of three photographs of Daniel during his evaluation of a soft prototype of a dynamic head support. His head was supported laterally and occipitally by the engineer. Just enough force was applied to maintain his upright head position, but very little additional fore was applied. These photographs show his range of movement during normal non-spasmodic use. In this case he is using his communication aid.

tions. Flexion/extension of the head was measured as a rotation about a horizontal axis normal to the sagittal plane, centred on a point a little behind the inferior larynx.

The evaluation of a soft prototype of a novel retrofittable dynamic head support by a young adult showed that it would be likely to benefit him in the following ways:

1. **Comfort:** The evaluator reported that the dynamic head support was more comfortable. When the research therapist misunderstood him and thought that he was saying the rigid support was more comfortable, he corrected her misunderstanding.

2. **Skin integrity:** The evaluator had an abraded patch on the back of his head from constant rubbing on his head support. This required frequent attention by his care staff. A dynamic head support would reduce this abrasion.

3. **Function:** The evaluator reported that he preferred using the dynamic head support when controlling his communication aid using head movement.

A separate retrofittable anatomical dynamic head support that provides the two stage support described in Section 12.3 may yield some of the benefits of a whole body dynamic seat to adults and children with a wide range of disability at a much lower cost than a whole seat. Such a head support may be of particular benefit when combine with a retrofittable foot support. See Chapter 13.

Chapter 13

A Dynamic Foot Support Concept

13.1 Introduction

This short chapter describes some preliminary work done on an independent dynamic foot support concept. The dynamic seat design includes a dynamic footrest. The team considered whether a simple independent footrest would be beneficial to adults and children with cerebral palsy and extensor spasms. A concept for such a footrest has been investigated in a small soft-prototype study conducted with the same adult with cerebral palsy who advised on the independent dynamic head support. In this thesis the participant is known as Andrew. The evaluation was video recorded.

If an independent dynamic footrest could provide some of the benefits of dynamic seating, it would be a cost effective way of improving seating for some people with extensor spasms, but who do not need a whole body dynamic seat. Some dynamic footrests are already commercially available, however these do not permit much movement, and are based upon the extensor thrust model of extensor spasm movement. Most have a vertically sprung platform which yields when the user presses down on it. The key difference between these footrests and the footrest proposed in this chapter is that the new footrest would be hinged at the knee and permit knee extension to occur. It would also permit plantar flexion to occur through the use of a footrest platform that could move radially away from the knee while maintaining contact with the foot. This approach to footrest design has been shown to be effective in the whole body dynamic seat that is the focus of this thesis. A sketch of the foot support as it was implemented in the second independent seat is shown in Figure 13-1.

13.2 Soft-prototype Evaluation

The project engineer and lead occupational therapist visited Andrew's workplace and planned a soft-prototype evaluation of the dynamic footrest concept. Andrew was seated in his wheelchair. After observing him in his wheelchair with his conventional footrests removed, the engineer and occupational therapist knelt either side of his legs. They supported his feet, simulating a plate beneath his feet and a heel cup, while allowing free movement at the knee. The support scheme is sketched in Figure 13-2

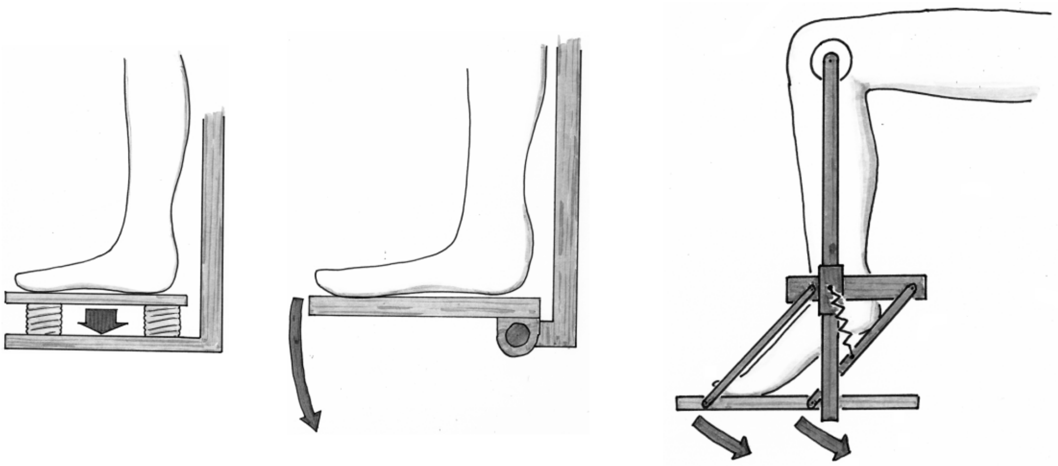

Figure 13-1: A diagram comparing conventional dynamic footrests *[LEFT and CENTRE]* to the proposed new independent dynamic footrest concept *[RIGHT]*, showing how it allows independent extension of the knees and plantar flexion of the foot while maintaining contact with the toes.

During the evaluation Andrew relaxed, and the team were able to support only his toes (with shoes) for much of the time. During spasms, his feet moved to his left, downwards and also rotated on a horizontal axis through the medial plane of the each foot. He also slightly extended each knee. The support scheme implemented was very similar to that adopted for the first independent seat which was being evaluated at the time. The foot was supported at the toes and the heel was allowed to lift during spasms. The supporters constrained the feet and resisted inversion and eversion (See Figures 13-2 and 13-3).

13.3 Evaluation Outcomes

The simulated footrest was very successful for Andrew. Several positive changes were observed while he was using it, which are described below. He also self-reported other changes using his light-pointer communication aid.

Head Control: Andrew's head control improved. This was due to reduced spasticity in his neck muscles, and improved posture. His ability to achieve control of fine movements (operating his communication aid) improved.

Whole body muscle tone: Andrew's background muscle tone reduced, particularly during intentional movement. A marked difference was observed in his arm position, which changed from being raised fully extended above his shoulder level at an angle of about 30° to the horizontal plane, to being relaxed and hanging by his side for much of the time and rarely moving above 30° from the vertical.

Spasm intensity and duration: Spasm intensity and duration decreased while Andrew was using the soft prototype. This was self-reported by Andrew and was also observed by the project team.

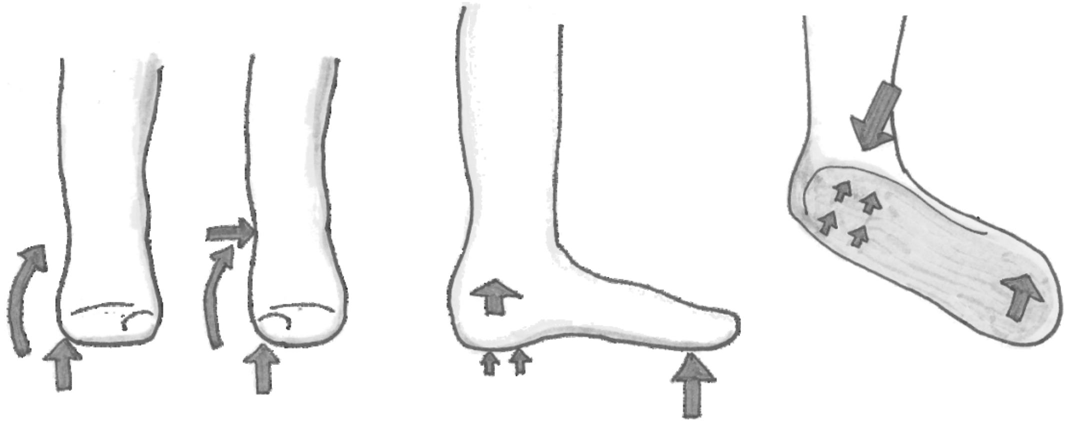

Figure 13-2: The support scheme implemented in the soft-prototype of the proposed independent dynamic foot support. This support applied a torque to the foot to correct inversion and eversion of the left and right feet respectively. The arrows show the torques applied by the research team.

Self reported changes: Andrew reported that the pain he experienced due to his muscle spasms was reduced, and in particular his neck pain was substantially improved. He has since repeatedly requested a prototype footrest to evaluate on a longer term basis.

13.4 Discussion

This present research has investigated the use of dynamic foot supports as an integral part of a whole body dynamic seat. The evaluation work carried out with all the physical and virtual seats that have been designed as part of this work has demonstrated that the appropriate support and constraint of the child's feet is critical to the success of a seat in reducing extensor spasm intensity and increasing comfort. The author has designed a new dynamic foot support (See Chapter 14) that has been shown to be effective in providing the right degree of compliance while maintaining proprioception and correct alignment of the foot.

Not all adults and children who experience extensor spasms do so throughout their whole body, neither do all experience spasms as powerfully or with such a large range of motion as the children participating in this research. The short study described in this chapter has briefly investigated the benefits of dynamic foot supports that can be retrofitted to an existing wheelchair. The study yielded surprisingly good results with an adult who has experienced extensor spasms all his life.

The observation of a reduction in whole body tone and increases in head and hand function in an adult with extensor spasms during the use of a (simulated) dynamic footrest of this design provides further evidence that the principle of Compliant Anatomical Support that the Whole Body Dynamic Seat is built upon is valid, and also that it is likely to be of benefit to larger adult and child populations beyond the severely disabled children that participated in the research.

Figure 13-3: Six photographs of Andrew in his wheelchair. *[1-3]* Photos 1-3 show a spasm in progress. His spasms were very powerful, but there was little movement visible. Note the eversion of his left foot. *[4-5]* Photos 4 and five show a lateral view of the support provided. For much of the evaluation session, it was sufficient to support only his toes, though sometime his left foot needed more support than this to maintain alignment. *[6]* Photo six shows Andrew in his wheelchair during a spasm. His arm in visible, raised from its usual position by his side.

13.4.1 Key findings

- Andrew gained almost immediate benefit from the foot support scheme implemented by the research team and designed by the engineer. He did not need to spend time learning how to use it.
- The foot support positively impacted his posture and head and hand function.
- The foot support significantly reduced his pain levels resulting from spasticity and spasm.

Chapter 14

The Design of a Second Independent Dynamic Seat

The second independent seat design, which evolved from the design of the first described in Chapter 10 was an attempt to simplify it, reduce its size and to start to design the seat for aesthetics. This chapter describes:

1. The technical evolution of the seat;
2. The product design concept developed for the seat;
3. The engineering design of the seat.

A photograph of the completed seat is shown in Figure 14-1.

14.1 Seat Design Evolution

The objectives of the design of the second independent seat were defined in response to problems and areas for improvement identified in the first independent seat. The evaluations in which these observations were made are described in detail in Chapters 11 and 4.

1. To move the seat towards a pleasing aesthetic design, reducing the presence of the seat and improving its shape;
2. To simplify the seat mechanism;
3. To implement virtual hinges on the hips and backrest;
4. To move the hip and backrest rotation centers to the hip joint axes;
5. To increase the range of height adjustment on the mobile base so a child using the seat could sit at a table.

Figure 14-1: A photograph of A1 working with the research occupational therapist.

All five of these aims were achieved, the first being confirmed by parents and staff who saw the seat when in use by a child at school.

The aims described in the list above were set as a result of observations made during evaluation of the previous seat. These observations are described in Chapter 10, but are also summarised below:

1. The first seat design was complex, machine-like and intimidating. Its appearance dominated the view of a child occupant, thereby distancing the child from other people who may have wished to interact with him.

2. The seat mechanism was complex, especially the hip mechanism. This was so that the torque characteristic experienced by the occupant was highly adjustable. When adjusting the spring preload and spring rate, it was found that the most of the large range of adjustment on both these factors was unused, so it was possible to reduce the range of adjustment and simplify the spring mechanism.

3. The first independent seat had thigh pivots co-axial with the child's hip joints. These pivots were large, and, as well as obscuring the child visually, also impeded the fastening of the lap strap.

   The backrest rotated on a pivot utilizing a plastic plain bearing and was not coaxial with the hip joint. The pivot was placed behind the backrest. This extended the length of the seat when the backrest was in an upright position.

4. It was found that if the backrest pivot was not co-axial with the hip joints, then shear would be induced between the child's back and the backrest when a spasm occurred and the backrest rotated backwards. This also caused displacement of the child's head support relative to his head position as the child slid down the backrest, raising the support distally away from the child's

neck during a spasm. This was particularly a problem with the Stealth i2i[52] head support which has a pair of lateral 'wings' which came forward over the front of the child's shoulders. These prevent the child from moving out from under the head support during a spasm, but if the support rises significantly, the wings create an upward shear on the sides of the child's head. This problem led to an alternative head support being used by R1 during evaluations of the first independent seat.

5. The range of height adjustment possible on the first independent seat was limited by the rear overhang of the spring mechanism impinging on the rear of the mobile base. The new design used a much more compact mechanism that was substantially below the seating surfaces, removing the overhang. This enabled the seat to be lowered so that the child's feet could touch the floor when in the seat; low enough for the child to kick a football while seated.

14.2 Product Design Concept

One of the aims of the second independent seat prototype was to consider the aesthetics of the seat and it emotional impact on its users, including children, their peers, school staff and parents and carers. To this end, BIME's product designer was recruited to assist with developing a concept for the seat. He provided methods that enabled the research engineer to develop a concept for the seat that was attractive and functional. The methods used were:

Concept statement A conceptual statement was made that described the desired impact and concept of the seat. This statement provided the foundation for the design of the seat.

Mood boards The engineer compiled a collection of images (mostly photographs) that represented the feel he wanted the seat to convey. These images translated the words of the conceptual statement into the visual domain.

Concepts The images were grouped into mood boards, from which were derived three concepts. Each of these concepts was translated back into a set of descriptive words.

Selection The word list from each concept was compared with the original conceptual statement, and the best aligned concept (words and images) was selected as a basis for the design of the seat. A phrase was written to sum up the selected concept.

Concept design The word and image collections were used as a basis for several concept sketches …

Design … which were engineered into detailed mechanical designs for the second independent whole body dynamic seat.

14.2.1 Concept statement

This work began with a concept statement for the seat. What was the reason for designing it? How did the designer want the user to feel while using it? What should it functionally achieve?

The guiding concept statement defining the aesthetic objective for the seat was as follows:

"Jonathan went for a walk in the hills with his father. His father held him and supported him as he sat on his shoulders. They waded through streams, crept through bushes, climbed rocks, dodged 'bears' and stalked deer. After they returned from their adventure, Jonathan remembered wading, creeping, climbing, dodging and stalking. He remembered how he felt when his father lifted him; the things he and his father talked about; and the feel of the water, the mud, the branches and the wind. It was a good feeling, and he wanted to do it again.

I want children like [R1] and [A1] to experience an adventure, to take some risks; and when they return, to remember what they did and who they were with, not how they did it. The seat should be a means to express who they are, experience an adventure and develop relationships."

This statement deliberately sets an objective that is unlikely to be achieved within the scope of the current programme of work, but it is important to know the direction in which the work is heading. Assistive technology enables the expression of capability and personhood; it is not about fixing problems. This research is about enabling the child to be a child, be a person, take risks, learn from mistakes, express creativity, express emotions, enjoy experience, nurture relationships and become a more complete and capable person. There is a long way to go.

14.2.2 Mood boards

A large collection of photographs was made. Included in it were pictures of bridges, aircraft, furniture, bodies and toys. Some of the photographs are shown in Figure 14-2.

14.2.3 Concepts

The mood boards were gathered into four concept groups, and words were assigned to describe them. The word at the end of each list described how the user might have related to the concept:

Aero: slender, strong, light; [wear]

Body: unconscious, enabling, dynamic, trust, exciting, security, danger, risk, support, encouraging; [body]

Bridge: elegant, soaring, inorganic, abstract; [use]

Skeleton: slender, lean, ribs, cool; [wear]

14.2.4 Select

The body concept was selected because it contained more feel and emotion than the other concepts. It was less about the seat shape, and more about the user's experience. It was a minimalistic concept that aimed for a body conforming functional design that receded out of the user's consciousness while in the middle of the adventure, much like a fully functional body would do. It was about relationship and

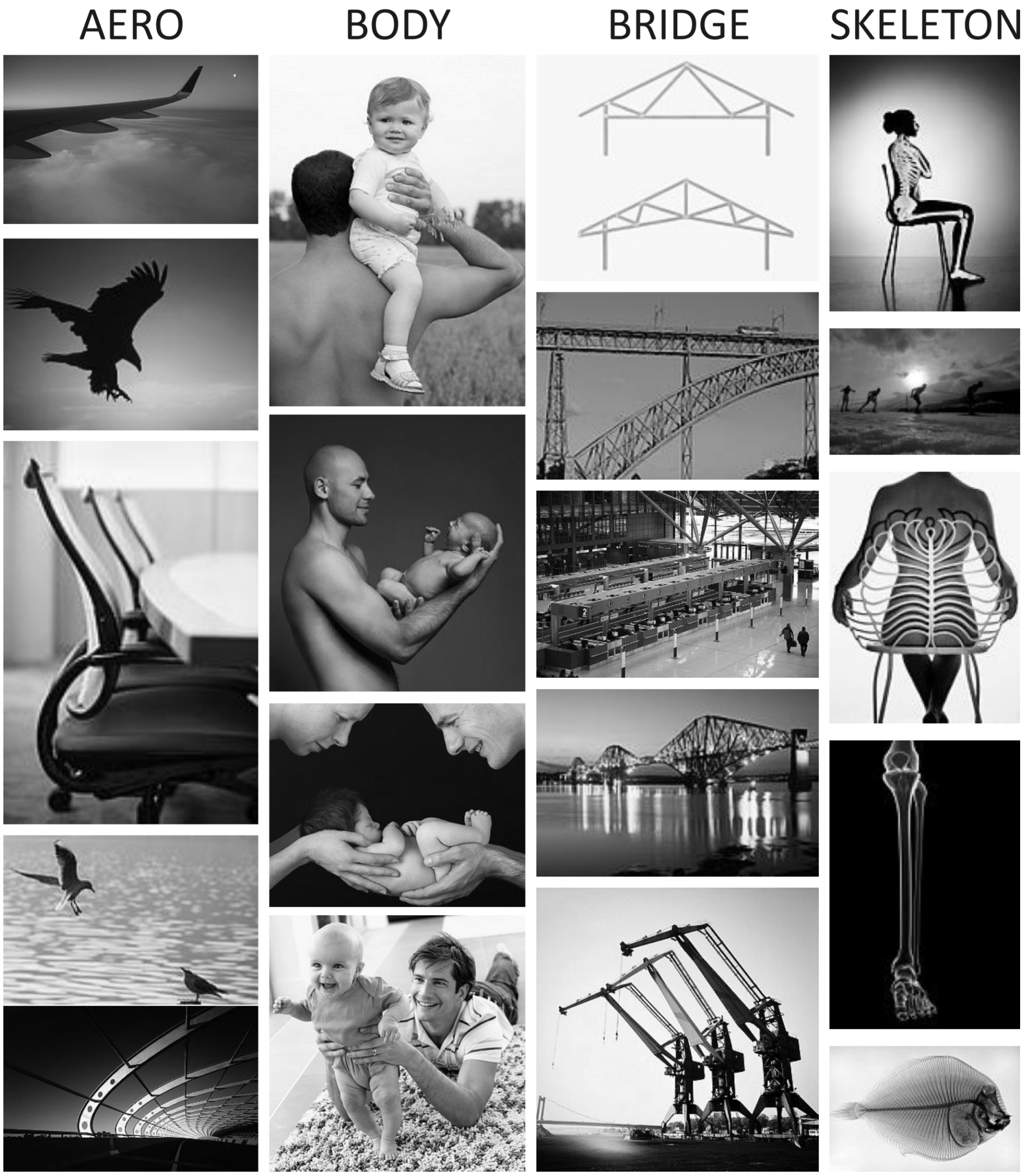

Figure 14-2: This montage shows some of the pictures collected for the concept mood boards in each of four categories: Aero, Body, Bridge and Skeleton. Each had a different feel and message to the viewer. Assembling the 'boards' were a way of understanding emotional reaction to shapes and forms that might have been used in the seat.

experience more than structure. The top photograph in the 'BODY' column of Figure 14-2 represented this idea well.

The other concepts were less about the people in the adventure, and more about shape and form alone. The did not carry the same emotional weight or excitement.

A phrase was written to succinctly express this concept:

"Remember the Adventure".

The seat user should remember what the seat was used for more than the seat itself, but the seat should still be remembered positively as one of the means to achieving the adventure.

This list of words was used intuitively to develop a colour scheme for a future seat:

Enabling: skin tones

Dynamic: green

Trust: green

Exciting: vibrant and primary / electric blue / red

Security: soft yellow / warm pink

Danger: orange

Risk: bright orange / icy turquoise

Comfort: warm pink / warm browns / muted burgundy

Support: strong / stone colour / steel colour

Encouraging:

14.2.5 Concept design

Sketches were made to express the chosen 'body' concept. These are shown in Figure 14-3.

These concept sketches were further developed into more fully formed designs as materials and mechanisms were investigated numerically. The sketch in Figure 14-4 is what was taken forwards to final engineering design.

14.3 Engineering Design

The conceptual design of the second independent dynamic seat was guillotined when it reached a sufficiently advanced stage so that engineering design could begin in time to build seat for long term evaluations before the end of the project. The design strategy was pragmatic, incorporating as many of the concept design outcomes as possible within the time available, but also working to reducing design time. Component costs were also an issue, but were less critical than time. This pragmatic approach resulted in the following decisions:

Figure 14-3: Sketches drawn to express the chosen concept. These designs employ 4-bar chain mechanisms to implement virtual hinges. These were later changed to segments of circular slides. Both designs used compact and conformal support surfaces that obscured as little of the child as possible. They also took into account what was likely to be achievable within the remaining project time. As a result they do not fully implement the desired concept, but are a significant step towards it.

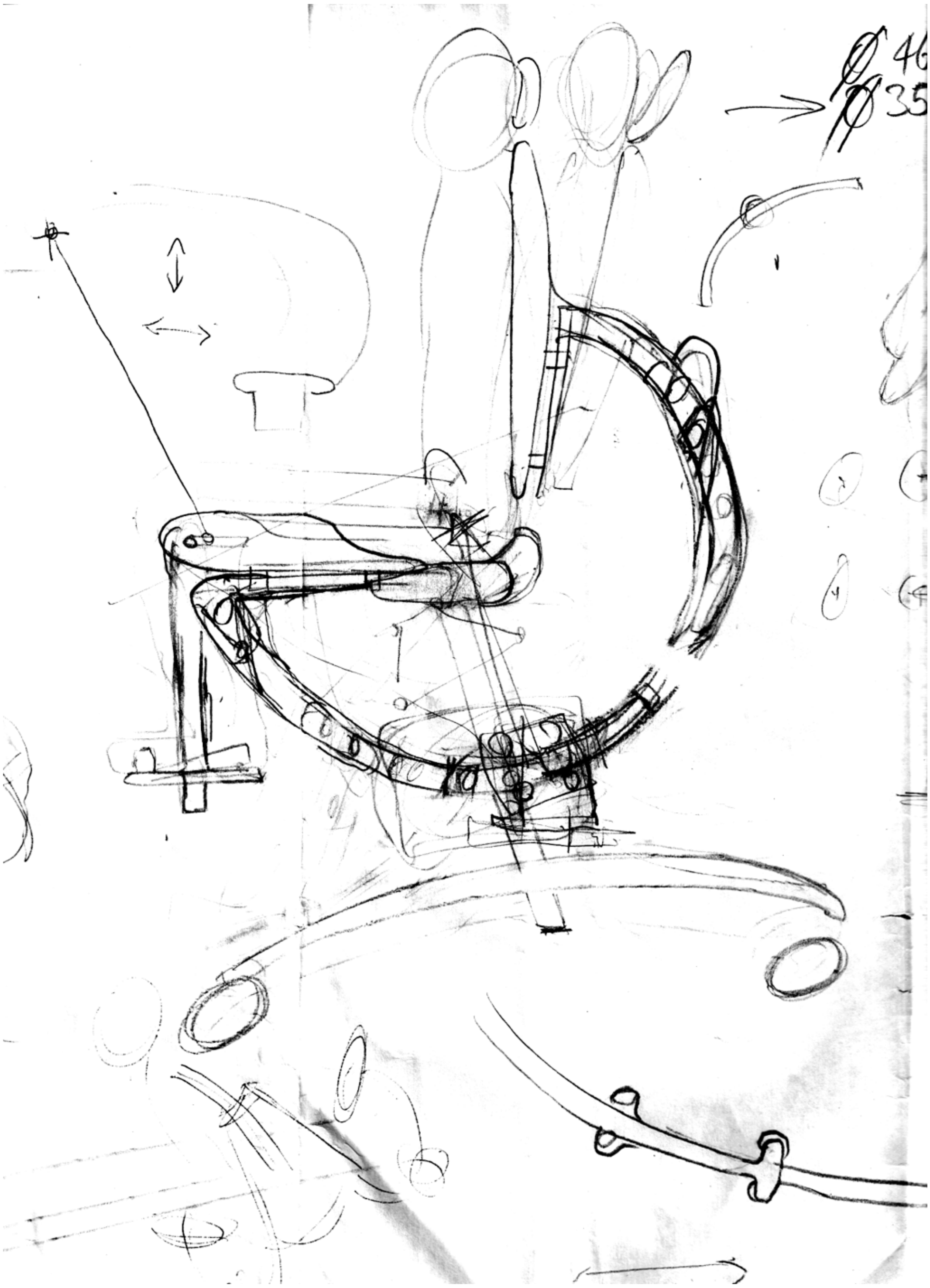

Figure 14-4: The final concept sketch, with virtual hinges implemented with circular slides rather than four-bar chain mechanisms.

1. Bought-in components were used wherever possible. Assemblies such as the seat backplate and lateral thoracic supports were reliable and aesthetic, though not always ideal. They were often considerably more costly than building similar in house.

2. The structural design of the seat was pragmatic. Less time was spent on structural optimisation than would have been ideal, resulting in heavier and larger components in some cases.

3. The aesthetic design of the seat was pragmatic. Less time was spent on achieving the desired forms than would have been ideal. This resulted in the seat looking more machine like and less attractive, potentially affecting the evaluator's response to it.

4. The manufacture of some parts was contracted out to local engineering companies. These parts were sometimes suboptimal in their finish and tolerances, but they were used where possible to maintain the design/build schedule.

5. Parts for two seats were made in parallel to save time, though only one seat was assembled. Where design changes were necessary after manufacture, two of each affected part were remanufactured rather than one.

14.3.1 Mechanical design specification

In response to the soft, semi-soft, and independent seat evaluations described in the Chapters 9 and 11, the functional specification for the seat was as follows:

Safety Specification

1. The seat should be safe for a child to sit in for extended periods. This requires minimising the risks of:

    (a) Impact with the ground after falling out of the seat;

    (b) Impact with moving parts;

    (c) Crushing from trapping by moving or static parts;

    (d) Skin damage from excessive pressure;

    (e) Skin damage from abrasion or shear;

    (f) Impact from the seat falling over;

    (g) Burn or electrocution from electrical systems;

    (h) Musculoskeletal damage from incorrect positioning;

    (i) Puncture or cut from sharp components.

2. The seat should be safe for staff to use in the classroom.

3. The seat should be safe for other children in the classroom.

Comfort specification

1. The seat should provide comfortable seating for the occupant.

   This requirement is one of the most demanding with the targeted population of children. The large forces generated by the children can easily cause discomfort on any restraining surface. See Section 11.5. Comfort is affected by the magnitude of external reactions to internal forces, and also by posture and internally opposed internal forces.

Movement and posture specification

1. The seat should support good posture in the child, and not contribute to the development of deformity.

2. The seat should yield to, rather than resist spasm forces.

3. The seat should stabilise the child's head and shoulders during spasms.

4. The seat should assist the child with maintaining an upright head position. This requirement supports social and educational engagement.

5. The seat should prioritise leg movement over back movement during spasms. This requirement reduces disruption caused to the child during spasms.

6. The seat should allow for a supporting surface to be provided in front of the child (either a tray fitted to the seat or a table moved to the required position).

Function specification

1. The seat should assist the child with maintaining an upright head position. This requirement supports social and educational engagement.

2. The seat should be height adjustable to levels similar to other wheelchairs in the classroom.

Classroom use specification

1. The seat should be adjustable by a non-technically trained user such as a therapist.

2. The seat should be able to be moved around the classroom and between classrooms.

3. The seat should be cleanable.

4. Transferring a child into or out of the seat should require no more than two adults.

14.3.2 Mechanical design description

This section is a detailed description of the seat, its design and function.

The user interface of this seat was very similar to the previous design, but it was implemented in a very different way. There was one important change made to the user interface, which was to move the backrest pivot from behind the user to make it coaxial with the occupant's hip joint centre, and almost coaxial with the leg support axis. Four views of the seat without its padding or head support are shown in Figure 14-5.

The seat comprised the following subassemblies and components:

Frame

The frame of the seat supported and positioned the key sub-assemblies; the leg supports, back support and weight bearing saddle. It comprised five sections of 40mm x 40mm square aluminium frame building section. The sections were arranged with a central spine on which two lateral sub-assemblies were attached. Their position can be adjusted forwards and backwards, changing the anterior / posterior position of the leg support.

Each of the lateral sub-assemblies comprises a lateral arm mounted perpendicular to the spine. On the rear face of the lateral arm, a lockable hinge joint is mounted incorporating a vertical axis hinge. The vertical axis hinge allows the abduction angle of the leg supports to be adjusted.

The hinge joint can be slid along the lateral arm towards and away from the central spine, adjusting the lateral position of the leg support.

A leg member is attached end-on to the hinge joint, roughly perpendicular to the lateral arm. Each leg member has a leg support mounted on its upper face.

A sketch of the frame assembly is shown in Figure 14-6

Weight bearing saddle: The weight bearing saddle is mounted on a vertical tube clamped to front of the central frame spine. The tube is height adjustable at the mounting point. The saddle can be adjusted forwards and backwards a little. The saddle is a women's bicycle saddle selected for its thick gel padding, short nose and wide pad. See Figure 14-7.

Mobile base The frame is mounted on a Jenx Gamma mobile base that provides a height and tilt adjustable mounting platform. The base is identical to that used on the previous seat, except that it has a slightly different mounting plate.

Leg supports

The left and right leg support assemblies support the child's legs. They are mirror identical, and are mounted on the top faces of the left and right leg support members of the frame. Positional adjustment of the leg supports is achieved though adjustment of the frame lateral sub-assemblies as described above. A sketch of the leg support assembly is shown in Figure 14-8.

Each leg support assembly comprises two main sub-assemblies: a leg support mount, and a hinged leg support. The leg support mount comprises a horizontal plate onto which is mounted a vertical

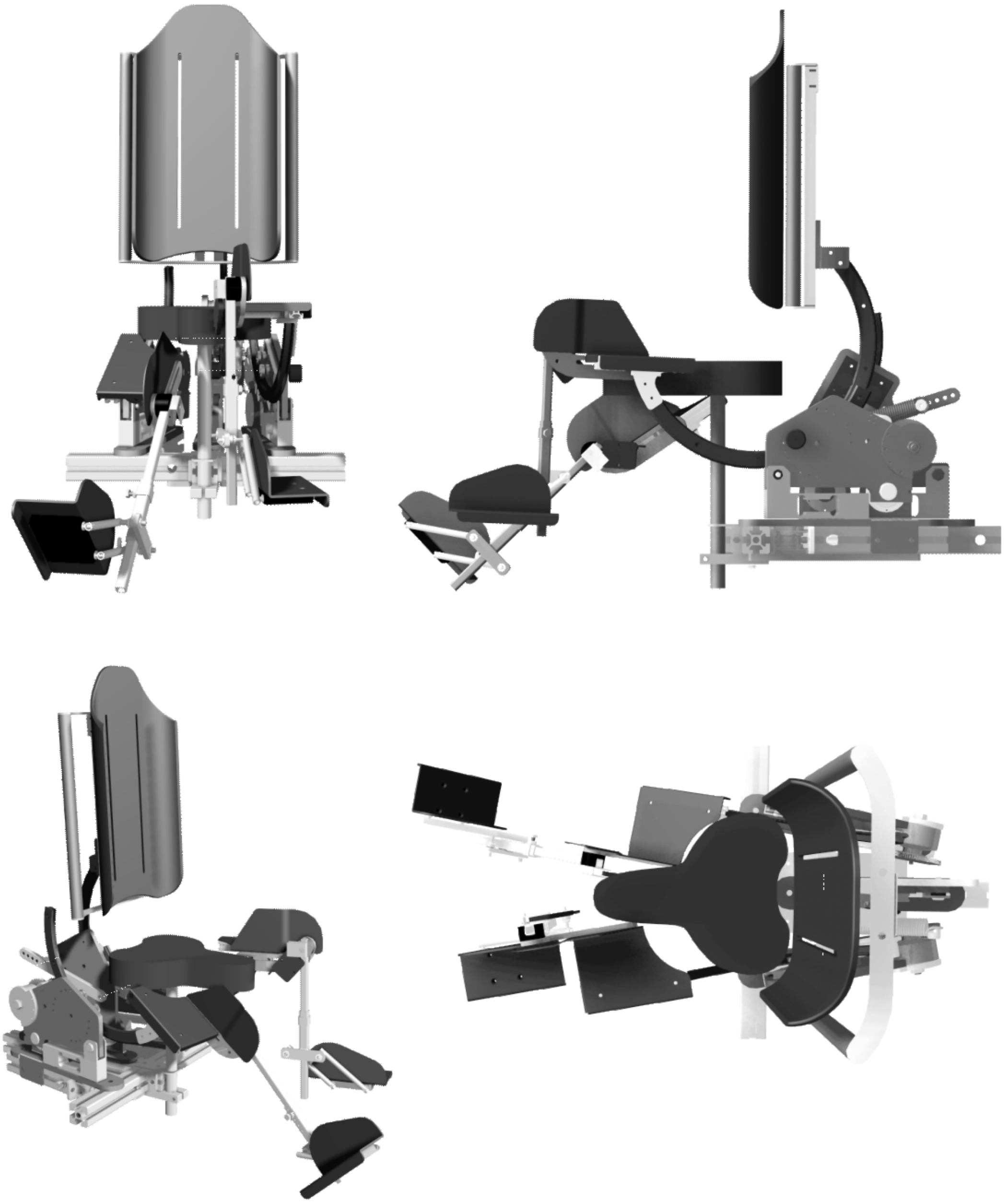

Figure 14-5: Four views of the second independent seat from CAD data, showing the support surfaces and mechanisms. These views do not show the Stealth i2i head support or the padding applied to the support surfaces.

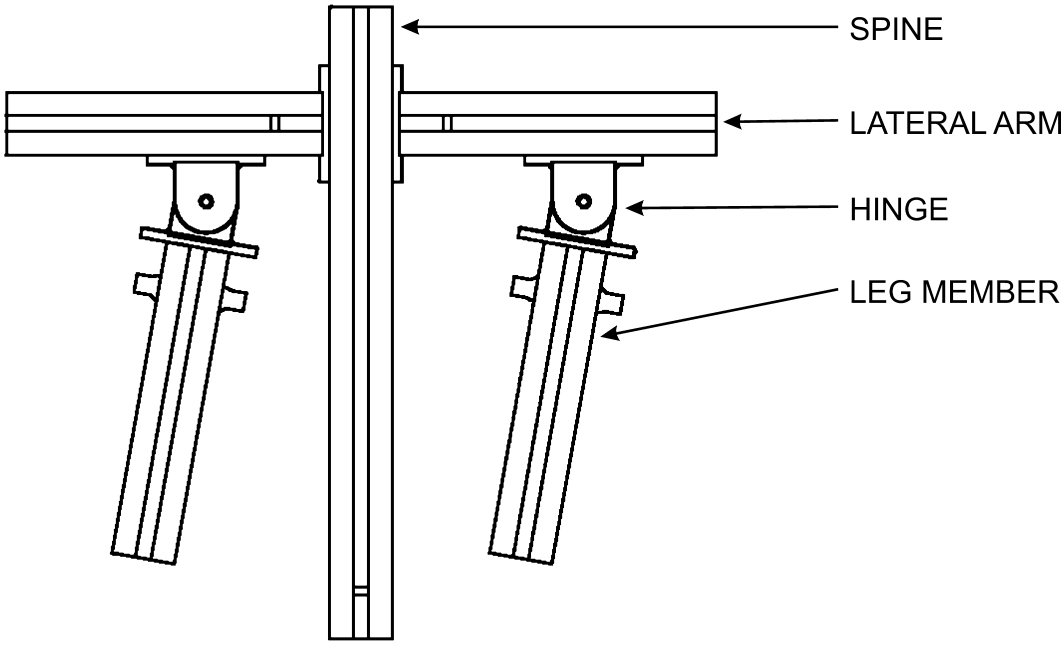

Figure 14-6: A drawing of the frame assembly from the second independent dynamic seat, showing the central spine (which supports the back support and weight-bearing saddle; and the lateral sub-assemblies, which support the leg supports.

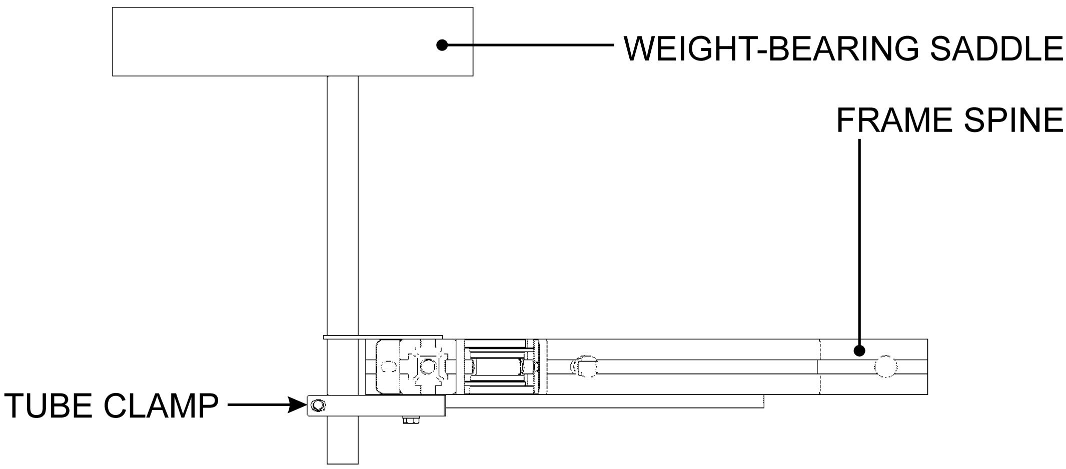

Figure 14-7: A drawing of the weight-bearing saddle mounted on the end of the frame spine.

plate, via a hinge and a load cell for the measurement of applied torques. On the vertical plate, a four roller carriage is mounted in which runs a corresponding segment of a circular slide that is part of the moving leg support. The carriage and slide together create a virtual hinge with a horizontal axis that can be aligned with the child's hip joint axis. The slide (a HepcoMotion 25mm PRT2 steel circular slide segment) was selected for its stiffness, high strength, free running and low maintenance. It is a high

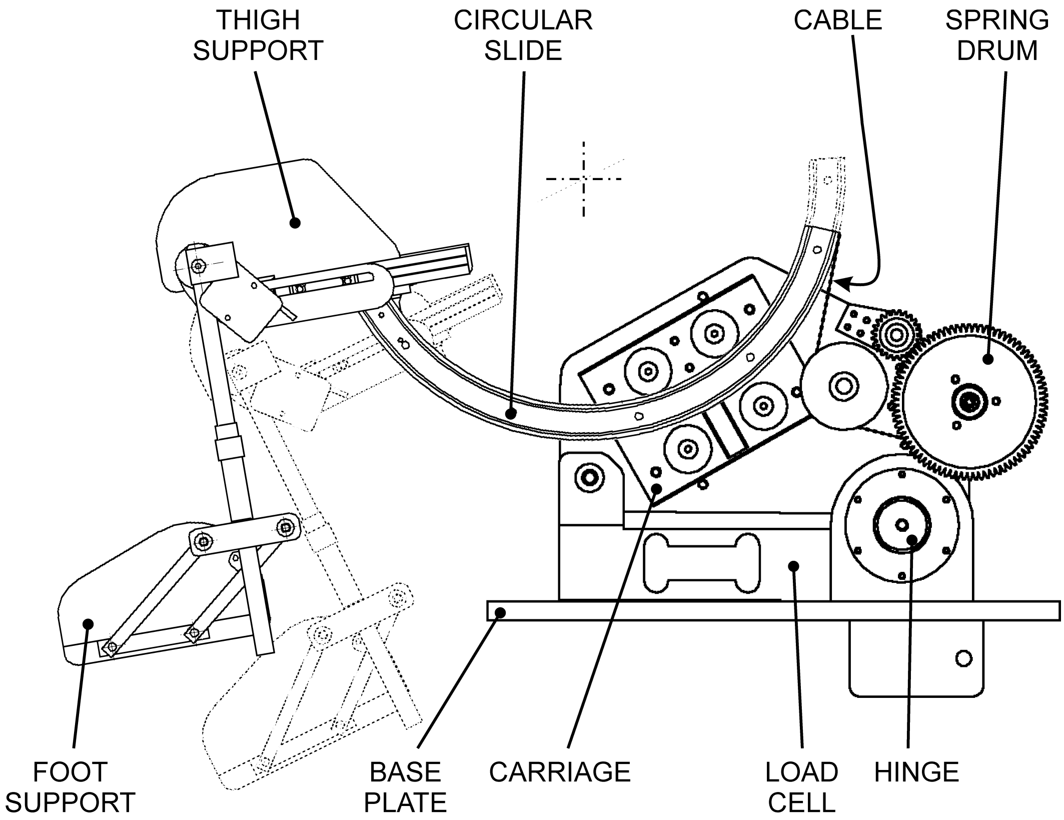

Figure 14-8: A drawing and sketch of the leg support assembly, showing the circular slide, and thigh and foot supports. The circular slide creates a virtual hinge at the indicated centre mark that is coaxial with the child's hip joint rotation centre, without requiring any structure around the child. This creates a more open feel for the child and means the seat has less visual impact.

quality industrial product that greatly exceeds the precision needed for this seat, however its use removed the need for a significant design effort to create a lower precision, lower cost slide. The disadvantage of this substantial slide is its inertia, which damps the seat response, and causes overrun and larger forces at the end of a spasm. An aluminium tubular slide would be much lighter and cheaper to manufacture, while still retaining sufficient stiffness and strength. The manufacturing cost and feasibility of such a slide was checked, but it was not designed.

As the front of the moving leg support is depressed during a spasm or volitional movement, a cable attached to the end of the slide unwinds from a sprung drum mounted on the leg support mount. The constant tension spring in the drum tightens as the cable unwinds, linearly increasing the spring force in proportion with the rotation of the moving leg support, and creating a mechanism to return the slide to its original position after the spasm has ended. Because a constant tension spring has been employed, the spring rate is low, and therefore the increase in force is small as the spring is wound up. This mechanism implements the requirement for a low spring rate in the leg supports.

Thigh support: The moving leg support has a slide which runs in the leg support mount carriage, onto one end of which is mounted a thigh support. The thigh support is a bent 'L' sectioned aluminium plate with an upwards pointing vertical face parallel to the sagittal plane and a horizontal face atop the end of the slide. The horizontal face supports the underside of the child's thigh and is shaped to fit around the side of the weight-bearing saddle. The vertical face extends beyond the distal end of the horizontal face, to provide a large surface which resists the child's adductor spasm.

Foot support: The foot support is hinged coaxial to the child's knee joint on a conventional hinge mounted on bracket medial to the vertical face of the thigh support. The hinge is not sprung, and its position can be adjusted in distal and proximal directions (forward and backwards). A bar is attached to the hinge, on which is mounted the foot support. The foot support can be adjusted up and down the bar.

The foot support comprises a platform which is attached to the knee joint bar by means of a parallel motion linkage that maintains the foot platform normal to the knee joint bar, while allowing it to move in an arc in the medial plane of the leg. The child's foot is anchored to the foot plate with a toe strap across the toes, and another strap that runs from below the distal foot, around the heel, to the below the proximal foot below the ankle. A medial lateral plate on the foot support prevents the foot from rotating at the knee. This arrangement secures the distal foot, while allowing the heel to lift from the foot plate during a spasm. A drawing of the knee and foot support mechanisms can be seen in Figure 14-9

Back support

The back support assembly is mounted on the top face of the frame central spine. It can be moved forwards and backwards on the spine, allowing its position to be adjusted relative to the weight-bearing saddle and the leg supports. Its height cannot be adjusted, and is set such that the back support rotational axis is at the same height as the leg support axes.

Back support mount: The base plate of the back support mount is bolted to the top face of the frame spine. It is similar in design to the leg support mount, but reversed front to back because torque is

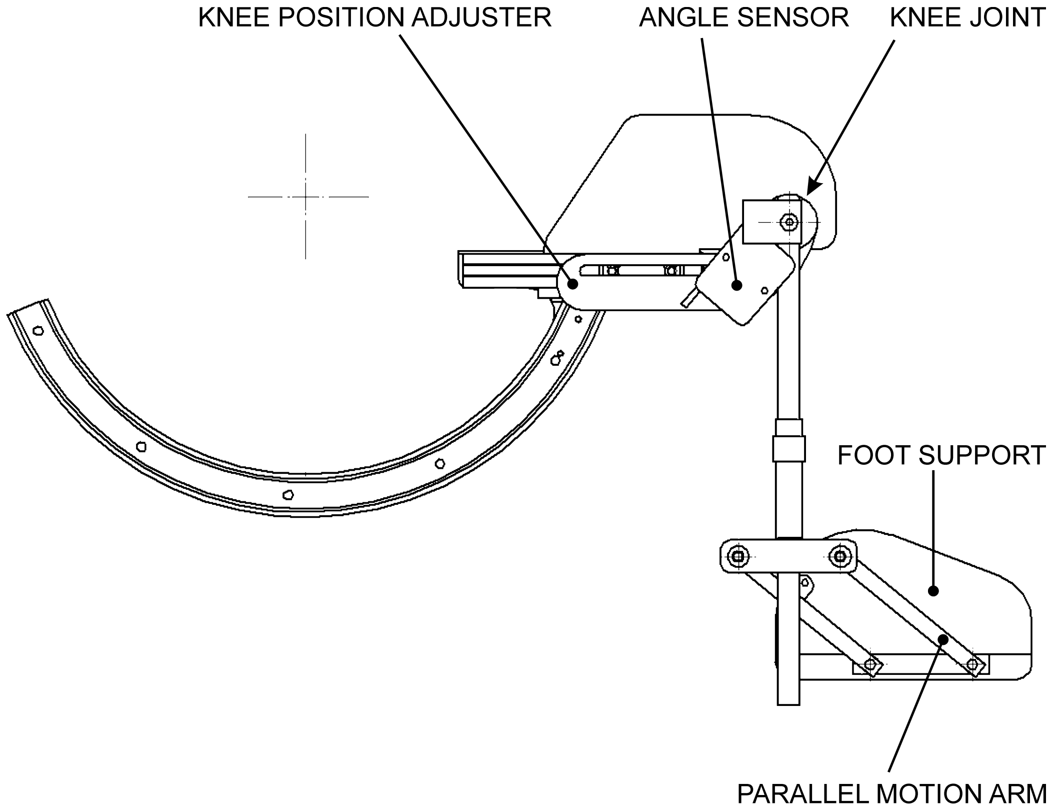

Figure 14-9: A drawing of the medial side of the leg support assembly. This drawing shows the knee joint with its distal/proximal adjustment; and the foot support with its sprung parallel motion mechanism that enables the child's heel to lift during a spasm.

applied to it in the opposite direction. The vertical plate is hinged on the base plate at the front of the base plate, and a load cell is built into the the back of the assembly to measure torques applied to the back support. A drawing of the back support assembly is shown in Figure 14-10.

A carriage identical to that on the leg support assembly is mounted on the vertical plate. A segment of a circular slide runs in the carriage rollers, creating a virtual hinge centred on the child's hip joint centre of rotation.

A helical tension spring is attached to the front of the slide and an adjustable lever on the back of the back support mount. The spring mount was positioned for maximum linearity of spring extension with backrest displacement. The spring has larger spring constant than the constant tension spiral spring on the the leg supports. This means that the force it applies to the backrest increases much more quickly with displacement than the force applied to the leg rest under similar displacements. This implements the required displacement bias in favour of leg movement over back movement during spasms.

Back rest: A rectangular frame with two lateral tubes is mounted on the end of the circular slide segment. It can be adjusted up and down in its position to accommodate variability in the length of children's backs. The frame is used to mount the back plate and its cushion, the lateral thoracic supports

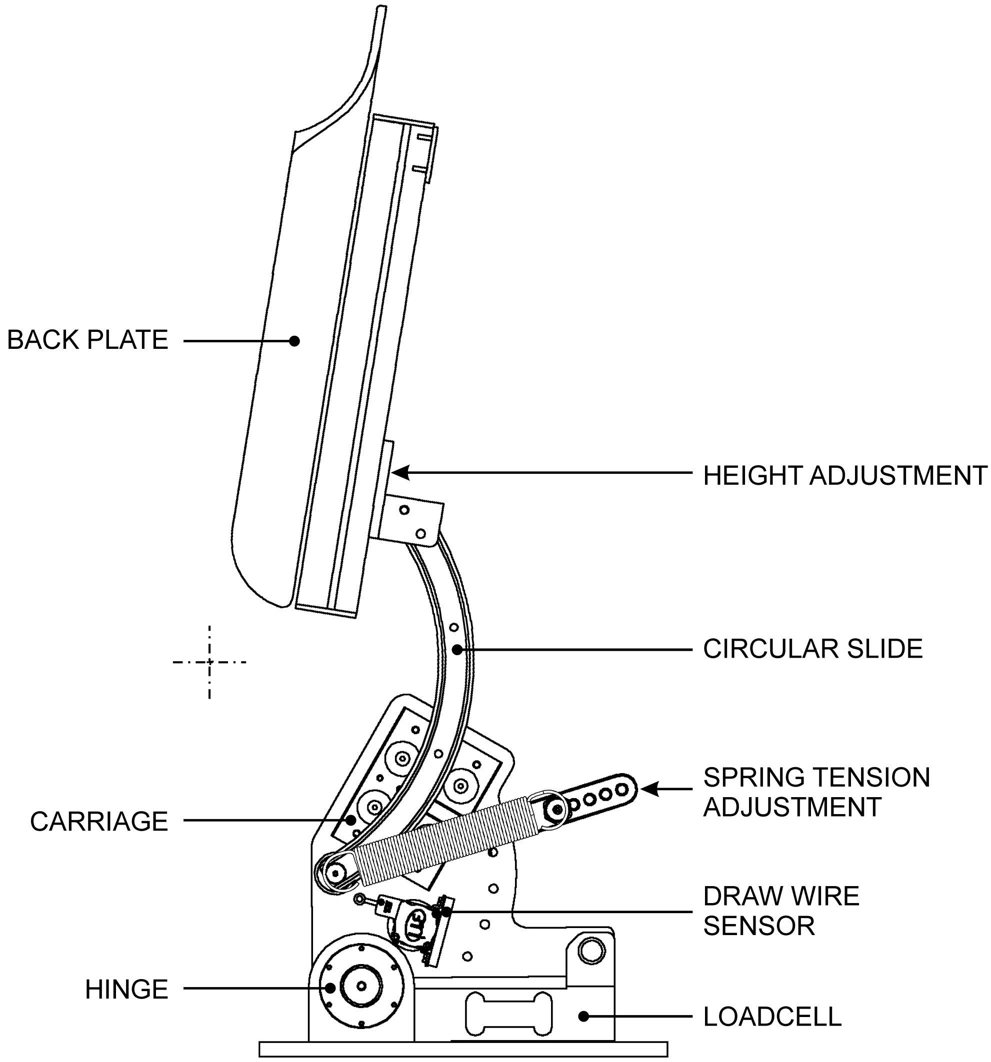

Figure 14-10: A drawing of the backrest assembly; showing the back support mount, the circular slide segment and the back plate. This drawing does not show the lateral supports or the head support. The centre of rotation of the virtual hinge is indicated by the centre mark.

and the head support. The aluminium back plate was bought in. It provides a contoured seat back with an air-filled cushion and a breathable mesh contact surface.

Lateral supports: The lateral thoracic supports were bought-in items as used previously on the first independent seat. They provide contoured lateral support and also a little anterior support. Their position can be adjusted up and down the back frame lateral tubes; and can be adjusted for width and angle of contact using their own mechanisms. The lateral supports can be seen in Figure 14-11. The lateral supports help to maintain postural symmetry and prevent skeletal deformity.

Figure 14-11: Three photographs of A1 in his seat, showing the head and lateral supports.

Head support: The head support was a Stealth i2i head support that provides sub-occipital support as well as some anterior support for a child with a highly mobile head. the head support can be adjusted for position and orientation in all directions. The head support can be seen in Figure 14-11. This head support provides much of the support needed for the head-up social engagement requirement.

14.3.3 Instrumentation design

The design of the instrumentation for this seat was very similar to that used for the previous seat. Because it measured the same parameters, it shared many components. Where the mechanisms of the two seats substantially differed, alternative sensors had to be found. The backrest and hip joint angles were measured by a draw-wire linear displacement sensor and multi-turn precision potentiometers respectively. See Figure 14-12.

For this reason, the description of the sensor system given in this chapter is abbreviated compared with that in Chapter 10.

Leg support measurement

The torques and angular displacements on the leg supports were measured using a variety of sensors (See Figure 14-13):

Leg support hip torque: This was measured with a load cell built into the leg support mount (see Section 14.3.2). Measuring torque at the base of the leg support assembly had both advantages and disadvantages (which also apply to the back support torque measurement):

Advantages

- The sensor and its supporting structure were well away from the child, reducing visual impact and improving ease of use.

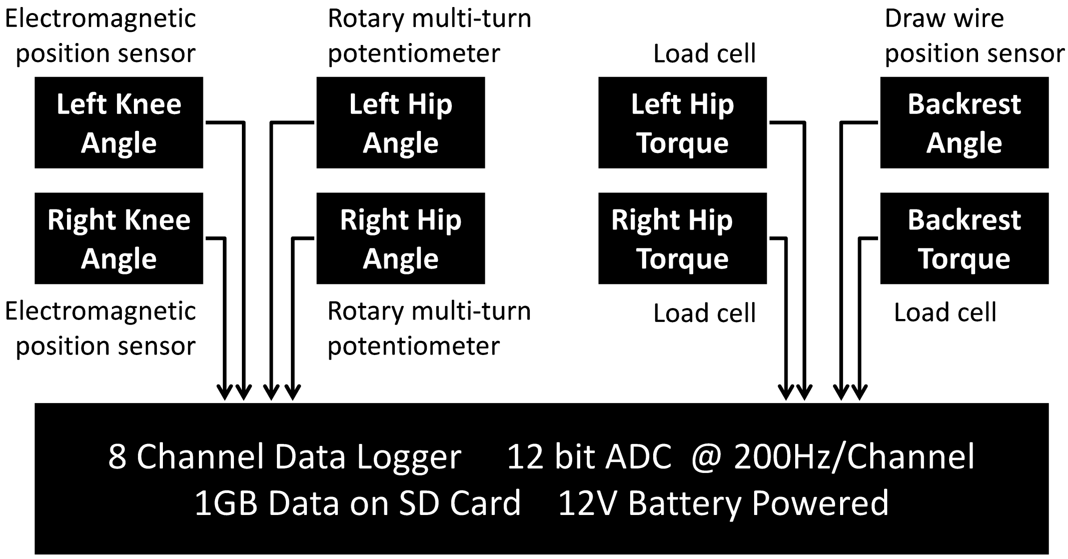

Figure 14-12: A block diagram of the sensor system for the second independent seat. Although fundamentally the system was the same as that used with the first independent seat, in differed in some of the sensors used because of the different mechanism design.

- The cell was well protected from damage to its flying lead and sensing elements.
- The leads from the sensor were not moving and so the conductors were less liable to fatigue fracture.

Disadvantages

- The load cell detected torques generated by oscillations of the seat structure functioning as an inverted pendulum when the child moved suddenly, as he did during spasms. These torques were overlaid on top of the torques resulting from the spasms.
- Calibration of the torque measurement was more complex because the centre of rotation of the load cell was different to the centre of rotation of the leg support. See Appendix B for a description of the calibration and an error analysis of the torque and angle measurements.
- The sensor would react to non-tangential forces applied by the child to the leg support.

Leg support hip angle: The leg support hip angle on the second independent seat could not be measured by the same means as in the first independent seat because there was no structure present on which to mount the magnetic blade sensor. Instead, angle was measured by measuring the rotation of the constant tension spring drum. As the leg support was depressed by the child, the spring cable was pulled by the end of the circular slide segment, unwinding the cable from the drum against the spring tension. The rotation of the drum was measured with a multi-turn precision potentiometer with a 10:3 ratio of potentiometer movement to spring drum movement. See Figure 14-14.

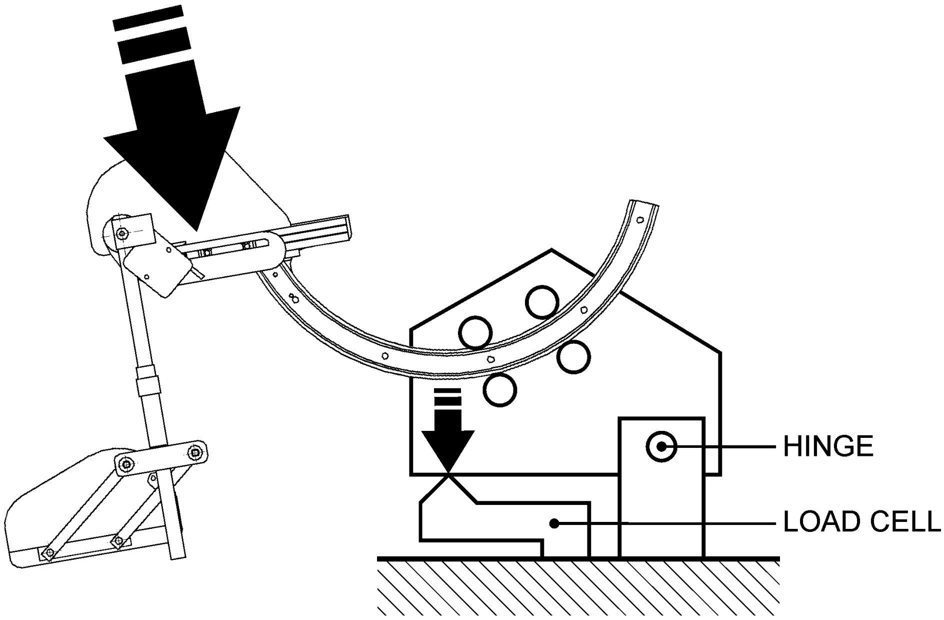

Figure 14-13: A diagram of the load cell mounting on the second independent seat.

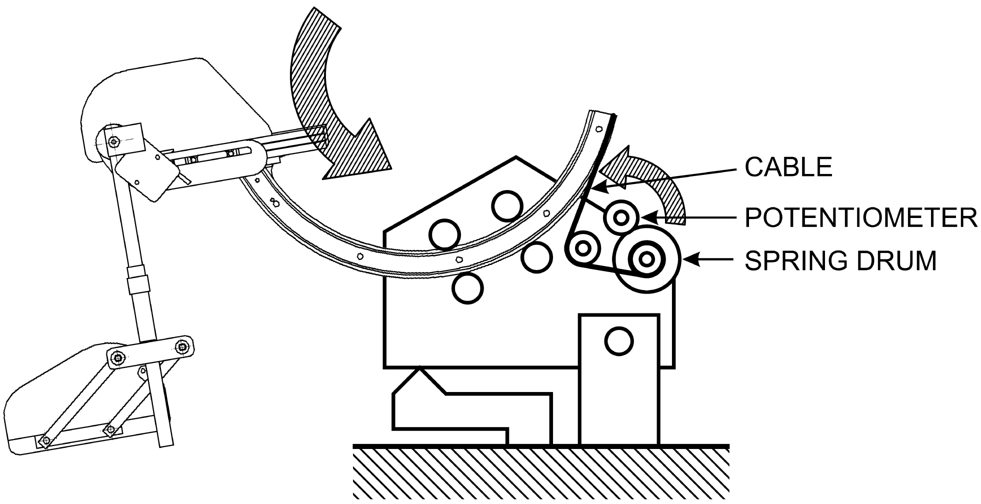

Figure 14-14: A diagram of the hip angle sensing system on the second independent seat.

Leg support knee angle: The leg support knee angle was measured using a magnetic blade angle sensor as in the previous seat. It was able to measure a range of 90° from full knee extension to 90° knee flexion. A diagram of the sensor installation is shown in Figure 14-15

Backrest measurement

The torque and angle of the backrest was measured with a load cell (torque) and a draw wire sensor (angle).

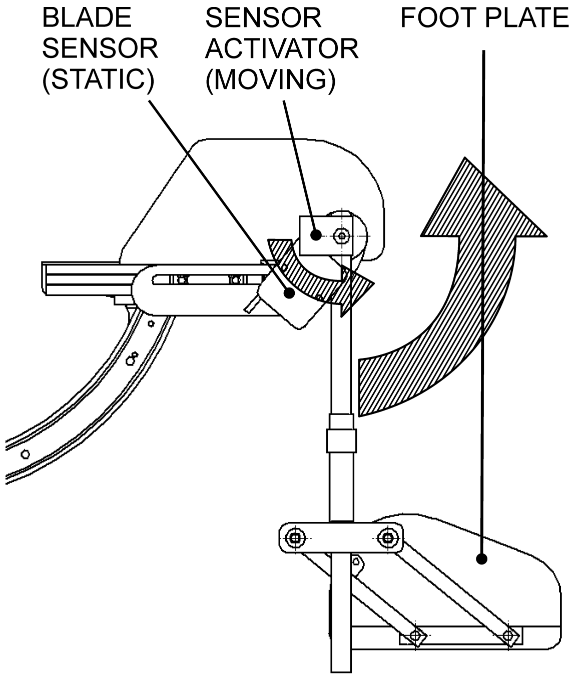

Figure 14-15: A diagram of the leg knee angle sensing mechanism. The '⋃' shaped sensor activator rotates over either side of the blade sensor, changing the inductance of the sensor as it covers it.

Backrest torque: This was measured with a load cell built into the base of the back support mount in a similar design to the leg support mount. The sensing method was identical except that because the backrest torque was applied in the opposite direction to the leg torques, the load cell and hinge were reversed so that the load cell would still be loaded in compression.

Backrest angle: The backrest used a simple extension spring to provide resistance to spasm torques. This prevented the displacement being measured with a potentiometer as in the leg because there was no spring drum. Instead, the displacement was measure with a draw wire sensor mounted on the back support mount and attached to the end of the circular slide. As the seat backrest was displaced by a spasm, the sensor string was wound into the sensor by its internal spring. The string to the sensor lay in a groove in the circular slide. A diagram of the sensor installation is shown in Figure 14-16.

14.4 Construction and Risk Assessment

The second independent seat was manufactured by an experienced technician at BIME and risk assessed by the author. The design and risk assessments were confirmed by the BIME principal engineer.

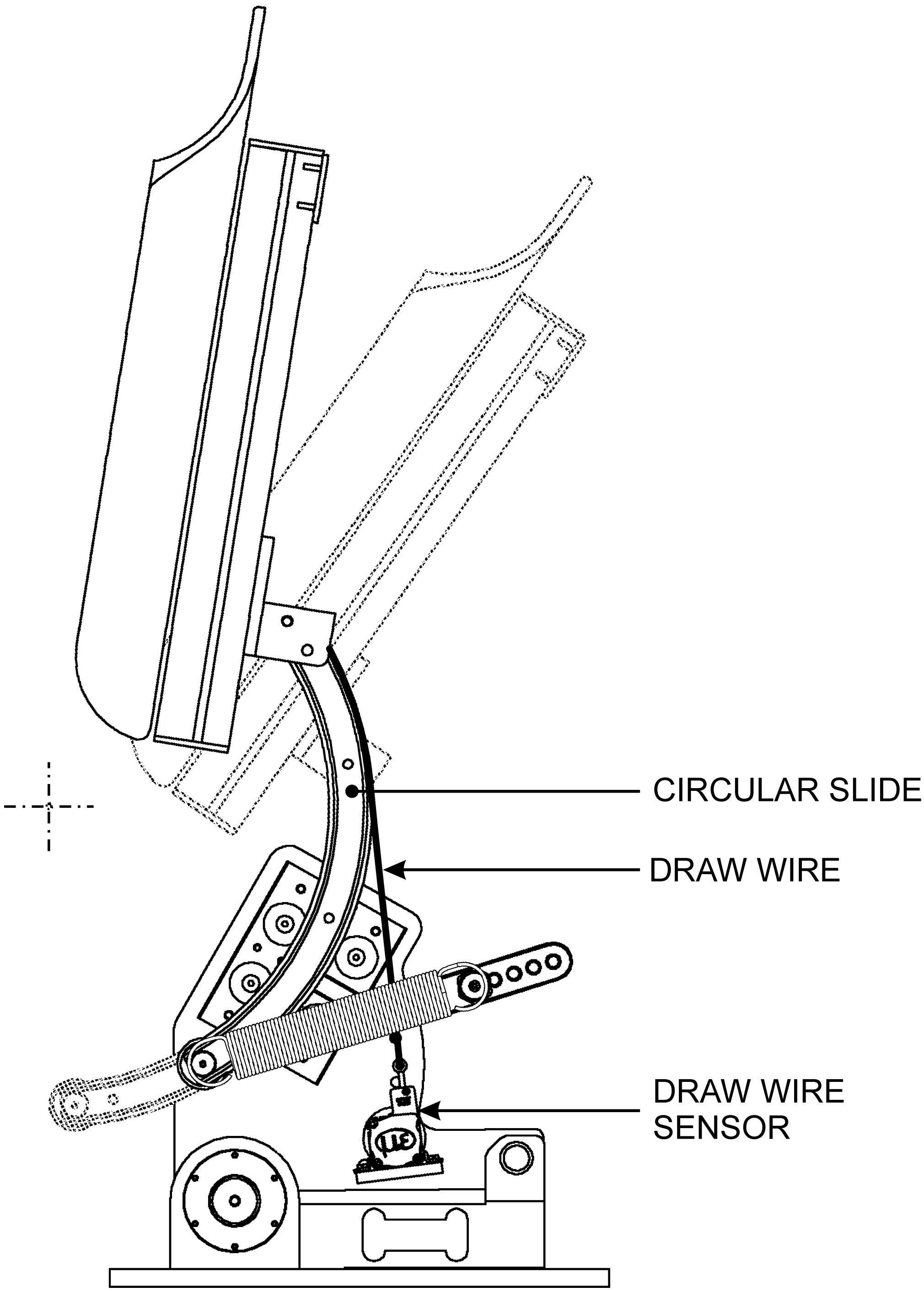

Figure 14-16: A drawing of the sensor installation for the backrest angle measurement. The cable which operated the draw-wire sensor was very fine, and lay in a groove in the circular slide for protection.

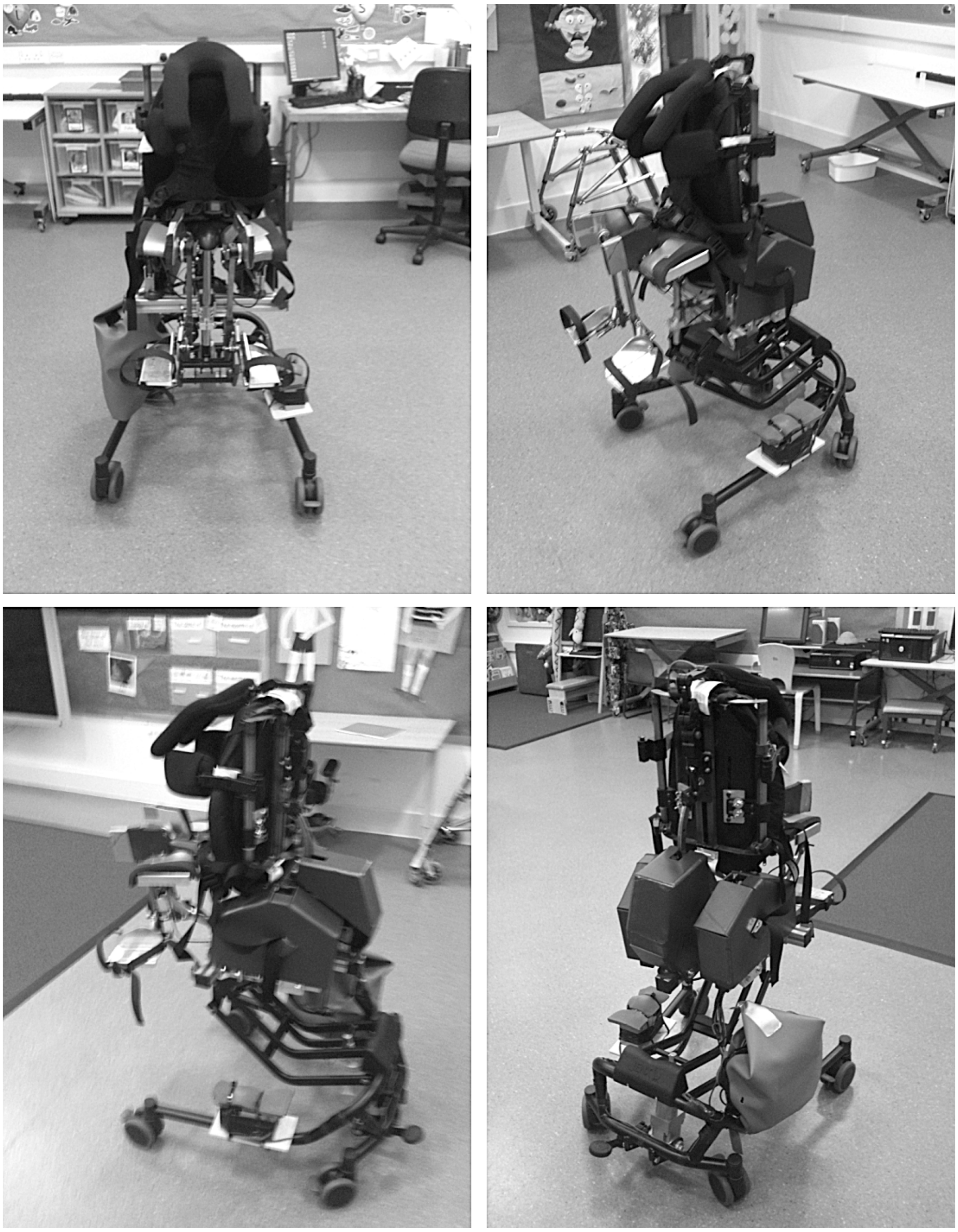

Figure 14-17: Four views of the completed second independent seat

Chapter 15

Evaluation of the second independent seat

This chapter's main purpose is to describe the evaluation of the second consolidated independent seat by child A1, and the conclusions drawn from the evaluation. However first it describes two small baseline studies carried out to provide comparison for the second seat evaluation to follow.

15.1 Evaluation 5, Baseline measurement and observations, A1, London, April 2011

Subject	Child A1
Dates	16^{th} April 2011 and 17^{th} April 2011
Duration	2 days
Location	Schools
Team	Occupational Therapist (Research)
Objective	To gather baseline data for A1 for comparison with seated study data.

Two short studies were carried out by one of the project occupational therapists at A1's school. The studies provided comparison data for the compliant seat studies. The first study (16-4-2011) was conducted at A1's school. He was held by his mother and video recorded. The research OT observed their interactions and analysed the video recorded at the time. The second study (17-4-2011) was similar in its method, and was also held in A1's classroom. A1 sat in his usual rigid seat and was observed and video recorded by the project research OT during a class circle time session.

The purpose of these studies was to increase the team's understanding of A1's movements when he was not constrained into a seat, and to enable observation of A1 when supported directly by his mother.

Figure 15-1: Four photographs of A1 being held by his mother during the baseline session in April 2011. The session was held in his classroom and lasted twenty minutes. TOP LEFT: Sitting in a flexed position without spasm. BOTTOM LEFT: Sitting extended during a spasm. TOP RIGHT: A1 sitting relaxed and engaged, looking at his teacher. BOTTOM RIGHT: A1's class teacher (right) discussing holding A1 with his mother.

15.1.1 Study 1, 16-4-2011: A1 on his mother's lap

A1 was held by his mother on her lap for twenty minutes while she sat on a low classroom seat. They played with a brightly coloured toy. A1 enjoyed sitting with his mother. He was comfortable and relaxed. While the camera was running, A1's teacher discussed with his mother how she holds and handles him at home. Figure 15-1 shows his sitting during the session.

A1's mother held him in a similar way to how R1's mother held him on her lap, sitting him in a flexed position on one knee, with her other knee providing lumbar support while her arm supported his upper back and head. When a spasm occurred, she allowed him to extend, moving her arm backwards and maintaining his position with his legs over one knee and his lumbar spine against the other. A1 was vocal during the session and was interested in the toy presented to him, however he did not engage with the toy using his hands.

During a three minute period in this session (05:50 to 08:50), sitting on his mother's lap, A1's head-up time was 52%. He was not engaged with either a toy or the people around him. He did occasionally look up to see what was happening when he was head down.

During the same period he experienced four spasms of 1, 14, 9 and 12 seconds duration. His total spasm free time was 80%. His spasm frequency was 0.02Hz.

15.1.2 Study 2, 17-4-2011: A1 in his usual seating

This study was conducted in A1's classroom on the following day. He was seated in his usual rigid seat, and participated in a group session with rhymes, music and musical instruments. He sat in a head up position until the attention of the group moved to another child away from him, and then sat head down for a time. He enjoyed interaction with his teacher. A1 was experiencing spasms in the seat. Some were quite prolonged and seemed to cause some, though not excessive discomfort. Figure 15-2 shows him sitting in the seat in spasm and when relaxed, and engaged with his teacher.

While in his rigid seat, A1's movements are severely restricted. When he extends, he seems to become 'fixed' against the straps in the extended position very quickly. This seems to prolong the spasm. He was able to enjoy participating in classroom activities while sitting in his rigid seat.

During a three minute period in the session, before the activity with his teacher (00:00 to 03:00), his head-up time was 92%. In a three minute period after the teacher's attention had shifted to another child (09:57 to 12:57), his head-up time was 89%.

During the first period, A1 experienced 4 spasms of 2, 20, 31 and 1 second duration. His spasm free time during this period was 70%. His spasm frequency was 0.02Hz. During the second period he experienced spasms of 2, 5 and 10 seconds (The last spasm continued beyond the end of the period and lasted 29 seconds). His spasm free time was 90%. It is likely that the increased spasm time in the first period is because of his heightened emotional state resulting from the activity preparation going on around him, and the engagement of his teacher as she introduced the activity. The prolonged spasm at the end of the second period began when his teacher returned her attention to him and discussed going to lunch, which he was pleased about. The spasm built gradually in waves, and then peaked, causing A1 to rise up in his seat against the straps.

15.2 Evaluation 6, Independent Seat v2: Child A1, London, 12-10-2011

Subject	Child A1
Date	12^{th} October 2011 to 1^{st} December 2011
Duration	6 weeks
Location	Combined Mainstream & Special Primary School, London
Team	Engineer (Research) Occupational Therapists (2 x Research) Child R1's teacher or supply teacher Child R1's occupational therapist
Objective 1	To assess Child R1's response to the second fully independent seat prototype in his usual classroom context.
Objective 2	To investigate the impact of the seat on A1's ability to function

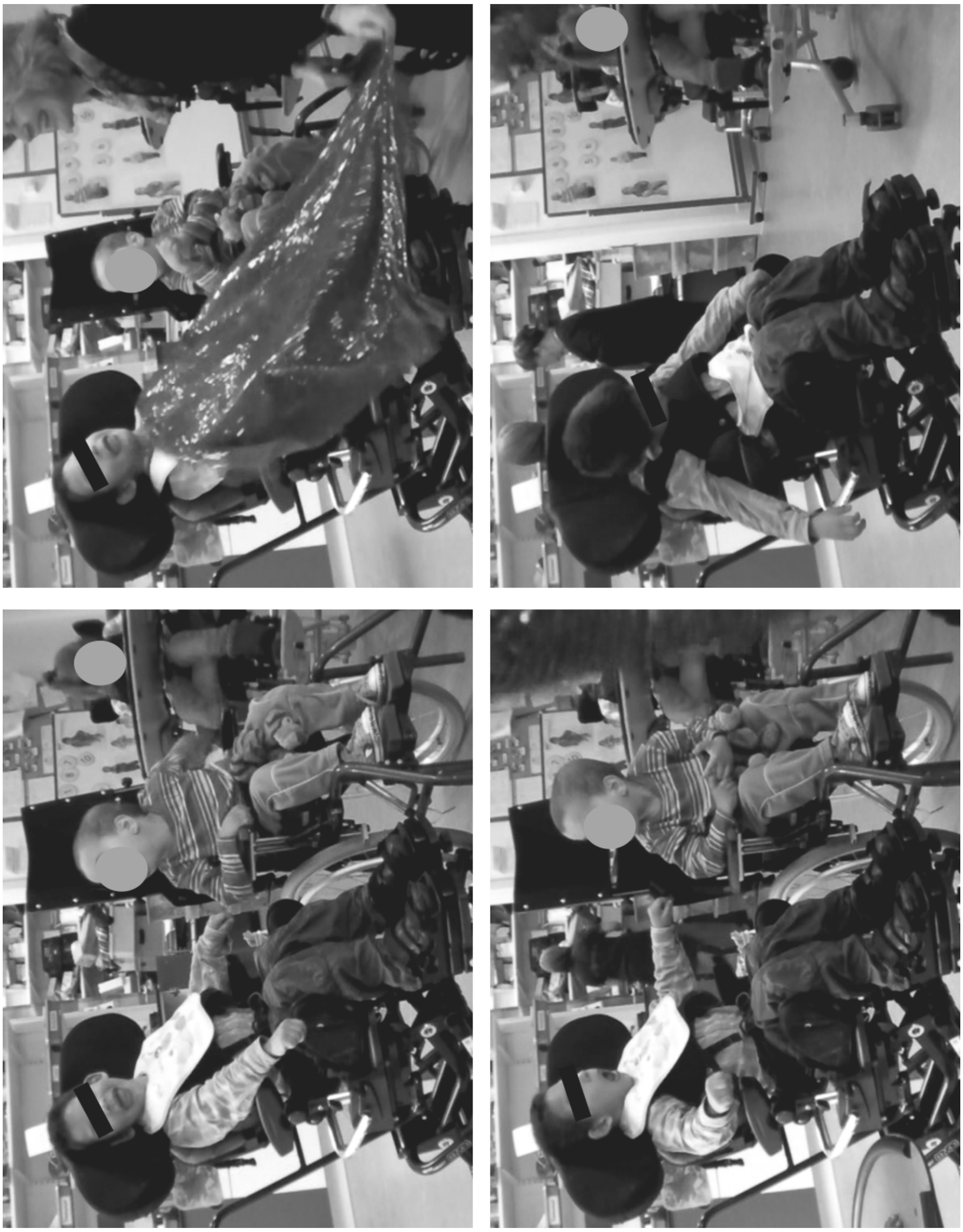

Figure 15-2: Photographs of A1 sitting in his usual rigid seat during a circle time activity in his classroom. The photographs show: TOP LEFT: A1 relaxed in his seat. BOTTOM LEFT: A1 during a spasm. TOP RIGHT: A1 engaged with is teacher during a game with a bright blue sparkly cloth. BOTTOM RIGHT: A1 disengaged after his teacher's attention has moved to another child.

15.2.1 Evaluation summary

The main aim of this evaluation was to evaluate the second independent dynamic seat over a longer period, to enable the user to become accustomed to using the seat. This evaluation took place in A1's school in London four weeks after the beginning of a long term evaluation *in situ* in his school. The team evaluated his function and posture in several different configurations. In between the first visit and the final visit, the right knee sensor was irreparably damaged. A1's usual teacher was absent on the 1^{st} December, so the class was led by a supply teacher. Key events in the course of the evaluation were:

12th October, Initial assessment and configuration: The seat was brought to A1's school for an initial assessment and configuration. It was brought back to BIME and the inner lateral thigh supports were moved and extended forwards to provide additional clearance between the supports and A1's crotch, and to provide additional medial support for his knees. This support was necessary because of A1's hip adductor spasm which was part of his whole body spasm pattern.

17th October, Delivery, training and initial assessment: The seat was delivered to A1's school and the classroom staff were trained in its use, including running the sensor system. The dimensions of the seat were set and fixed. The staff were asked not to modify them. The seat was evaluated in its locked and unlocked configurations. These sessions were video recorded, however the sensor data from the sessions was later lost due to an accidental reformat of the memory card while in the data logger. Subsequently data was uploaded to a computer after every session in which the research staff were in attendance.

7th November, Occupational Therapist Assessment: One of the project research occupational therapists visited A1's school in the middle of the evaluation to check that the evaluation was proceeding satisfactorily and also to assess A1.

1st December, Evaluation end and final assessment: The evaluation ended with a visit to the school by the research engineer and both research occupational therapists. A full school day was used to assess A1 in his usual static seat as well as in the dynamic seat, with the backrest free and locked. His hand function was assessed in his static and dynamic seats.

12th December, Collection and refurbishment: After the completion of the evaluation work, the seat was collected and returned to BIME for refurbishment and modification. The modifications made were:

- *Add a push handle:* the seat needed a push handle to enable it to be easily moved around and between classrooms.
- *Add a tray:* It was found that A1's head control and hand function improved when placed with a table before him. For this reason a demountable tray was added to the seat.
- *Enable joint locking:* The backrest and hip joints were made lockable to ease transfers into and out of the seat.
- *Remove sensors:* The sensor system was removed as it added unnecessary complexity to the seat.

- *Apply protective coatings:* The metallic components of the seat were powder coated with plastic to provide a durable and aesthetic finish.

April 2012: Delivery and long term use: The seat was returned to A1 in April 2012 for use in his classroom, where it currently remains. A1's teacher compiled a short report on his progress with the seat in June 2012. See Section 15.4.

15.2.2 Seat setup and initial assessment - 12th October and 17th October

On this day the seat was initially evaluated by A1 in the physiotherapy gym at his school. The most significant finding of this evaluation was that A1 enjoyed sitting in the seat. He enjoyed the movement of the backrest and leg supports, and giggled as he moved. The large pieces of foam hanging out from the side of the thigh trays have been added to provide additional padding for his thighs, which were impinging on the proximal edges of the abduction plates. He sat well, with good head control and active social engagement with the evaluation team. See Figure 15-3. The leg springs were set to start to yield under a load of 3kg at the distal end of the thigh supports.

The headrest used on the dynamic seat was a Stealth i2i Small[52] (See Figure 10-6). This is an unusual design of headrest with as continuous occipital support that extends over the shoulders and down the chest of the child. It was selected for A1 during the previous evaluation as he did not have sufficient head control to maintain position on a more conventional support. The i2i support prevented his head from becoming caught behind or beside the headrest.

Changes made to the seat on this day were:

1. The seat was adjusted for size to suit A1. This remains a complex task.
2. Padding was added to the thigh trays during the evaluation.
3. The medial lateral supports for the thighs were found to be too short. The thigh trays were remanufactured for the next session, with longer medial laterals and more clearance between them and the weight bearing saddle.

The evaluation of the seat in its locked condition conducted towards the end of this session showed A1 sitting in the seat in a similar way to his static seat. He was still experiencing spasms, but they were much harder to see than when the seat was unlocked. It is disappointing that the sensor data from this session has been lost due to an accidental memory card reformat by the project engineer. On the data logger, a short press (1 second) of the single control button starts logging, and a long press (3 seconds) reformats the card. This data would have enabled a quantitative comparison of spasm strength to have been made with the locked and unlocked configurations.

15.2.3 Classroom use - 18th October to 30th November

The seat was in regular daily use when A1 was in school between the 17th of October and 1st of December. His usage was video recorded. During this time he participated in normal classroom activities in the dynamic seat.

Figure 15-3: A video still of A1 sitting in the second independent seat prototype during the first set-up session on 12^{th} October 2011. He enjoyed the movement of the backrest and leg supports, and giggled as he moved. The large piece of foam hanging out from the side of the thigh tray has been added to provide additional padding for his thighs, which were impinging on the proximal medial abductive faces of the trays. He sat well, with good head control and active social engagement with the evaluation team.

15.2.4 Final Evaluation - 1st December

The final assessment directly compared A1's sitting and function in his usual static classroom chair with his sitting in the new dynamic seat. The configurations investigated are shown in Table 15.1.

Table 15.1: A table showing the order of the configurations investigated during the December 1^{st} evaluation of the second fully independent seat prototype. This evaluation compared A1's posture and function in his static seat with his posture and function in his dynamic seat.

Seat	**Table**	**Movement possible**
Sitting on therapist's lap	No table	Free movement
Dynamic seat	No table	Backrest and legs free
Dynamic seat	No table	Backrest locked, legs free
Dynamic seat	Table	Backrest and legs free
Static seat	Table	Backrest and legs fixed (usual static seat)

A1 changed his status in the year since the previous evaluation, and was sitting more comfortably in his static seat. However he was still experiencing whole body spasms resulting in some problems with his static seating.

A1 was observed in his static classroom chair. It appeared to offer a comfortable position and his head control was good. However he had some rotation in his trunk in this seat, which could lead to scoliosis (a permanent curve of the spine). When sat in the dynamic seat, A1 was more symmetrical and sat without the truncal rotation, although his contact with the backrest was less. During our observation the lack of contact with the dynamic seat backrest wasn't considered to be a problem though it it did worsen during spasms. Locking the dynamic seat backrest did not noticeably improve or worsen its contact with A1's back; however this did remove some of his functional gains.

Positioning a table in front of A1 provided spatial and emotional security for him. He used the table surface to provide stability, and as a supportive surface to assist interactions with a switch.

He exhibited some lower spinal extension, but this was not thought to be a problem as he was sitting more symmetrically than in his rigid seat, with less pelvic rotation.

A1's class teacher observed that his hand function improved when using the dynamic seat, compared to his static classroom seat. Further investigation confirmed that his hand function improved when attempting to operate a switch, through the use of a whole body arm pattern. He was using movement enabled by the dynamic seat to bring additional control to his hand position, adjusting the recline of the backrest to move his hand forwards. Conversely, in the static seat, his upper body was 'locked' by the fixed position of his seat. He also seemed to experience a succession of Asymmetric Tonic Neck Reflex (ATNR) and Symmetric Tonic Neck Reflex (STNR) spasms while sat in the static seat that were not observed while he was in the dynamic seat. These spasms further locked his upper body movement and inhibited functional movement of his arms and hands.

Observation of A1 in both seats led the research and school therapists to the conclusion that the best choice of seat for him at that time depended on the activity that he was engaged in. He was able to sit in his static seat (this was a considerable improvement on the previous year's observations), however the compliant seat offered better support for functional activities using the upper body, and increased his social engagement.

Preparation for the Final Evaluation

Preparation for this evaluation was minimal, as the seat was already in use in the classroom. The seat sensors were switched on and the video cameras were set and positioned to record anterior and lateral views. This was so that they would capture the seat movement, facial expression, head and hand movement.

The seat was positioned in front of the classroom screen where a familiar children's television programme was shown (BBC CBeebies 'Something Special'). A1 was lifted into the seat and secured in place using the lap strap and BodyPoint harness. Two people (the research therapist and class teacher) were needed to put him into the seat. One lifted him into position in the seat and held him securely while the other secured the lap strap. Once this was in place, both the therapist and teacher secured the remaining constraints and supports.

A Note on Manual Handling: Putting A1 in his seat highlights an issue due further research. The manual handling of children into and out of seating and other supports usually requires at least two people for the procedure to be safe for the child and the supporters. Most parents of disabled children do not have the benefit of a full-time helper to assist with lifting and transfers at home and many suffer chronic back injuries as a result. Seating should be designed with transfers in school and home environments in mind.

Evaluation

Video recording was started before A1 was placed in the seat, and data capture was started once he was in place and secure. In the morning the team investigated his function and posture in the dynamic seat with free movement, partially locked at a table, and free movement at a table. In the afternoon the team investigated his posture and function in his static seat while sitting at a table. Both sessions were video recorded.

Dynamic Seat - Free movement: A1 was seated in the dynamic seat. He sat comfortably in the seat while being observed. Figure 15-4 shows him in flexed and extended positions at rest and during a spasm respectively.

During this session, the research team investigated his functional vision through his engagement with a number of different toys as his classroom team were considering obtaining eye-tracking software and hardware for him. A1 was much more reactive to auditory than visual stimulus. For much of the evaluation he was watching a television programme. During this period he also demonstrated volitional reciprocating gait-like movements - See Figure 15-5.

Dynamic Seat - Locked backrest: A1 continued to sit in the seat. The backrest was locked in the upright position, preventing any movement. The hip and knee joints remained free. The seat backrest was locked at twenty seven minutes into the session and the effect of locking it was observed.

Figure 15-4: Video stills of A1 sitting in the dynamic seat flexed (LEFT) and extended (RIGHT) not long after he was placed in it on the morning of the 1st of December 2011. This movement was a spasm, but he made more smaller movements which are thought to be volitional.

He tended to sit with his head forward more frequently and did not maintain an upright head position as well. In a clear two minute period shortly before locking the backrest, his head was upright for 86% of the time. During a clear three minutes period shortly after the backrest was locked, his head was upright for 67% of the time. A1 can be seen in a head down position after locking the backrest in Figure 15-6.

Dynamic Seat with table - Locked backrest: The backrest was unlocked, and a variable height table was positioned in front of A1 just below his elbow height. He placed his hands on the table and extended his arms, partially weight bearing upon them. This position gave his upper body additional stability and improved his head control. The introduction of a table in front of A1 changed his movement pattern again. A sample of this data is shown in Figure 15-7.

A1 attempted to operate a switch held in front of him while seated at the table. After much effort and concentration he achieved this with help from his teacher, who positioned the switch higher so he could reach it. It took him fifty eight seconds to move his hand to the right place to operate the switch.

A1's head control improved with the addition of the table. His head up time for the three minutes before the table was introduced was 50%. His head up time for the three minutes after the table was introduced was 90%. The table made a significant positive impact on his ability to remain engaged with his environment.

Dynamic Seat with table - Free movement: The backrest was unlocked, and a variable height table was positioned in front of A1 just below his elbow height. He placed his hands on the table and extended his arms, partially weight bearing upon them. This position gave his upper body additional stability and improved his head control. A significant outcome of this session of the evaluation was the observation

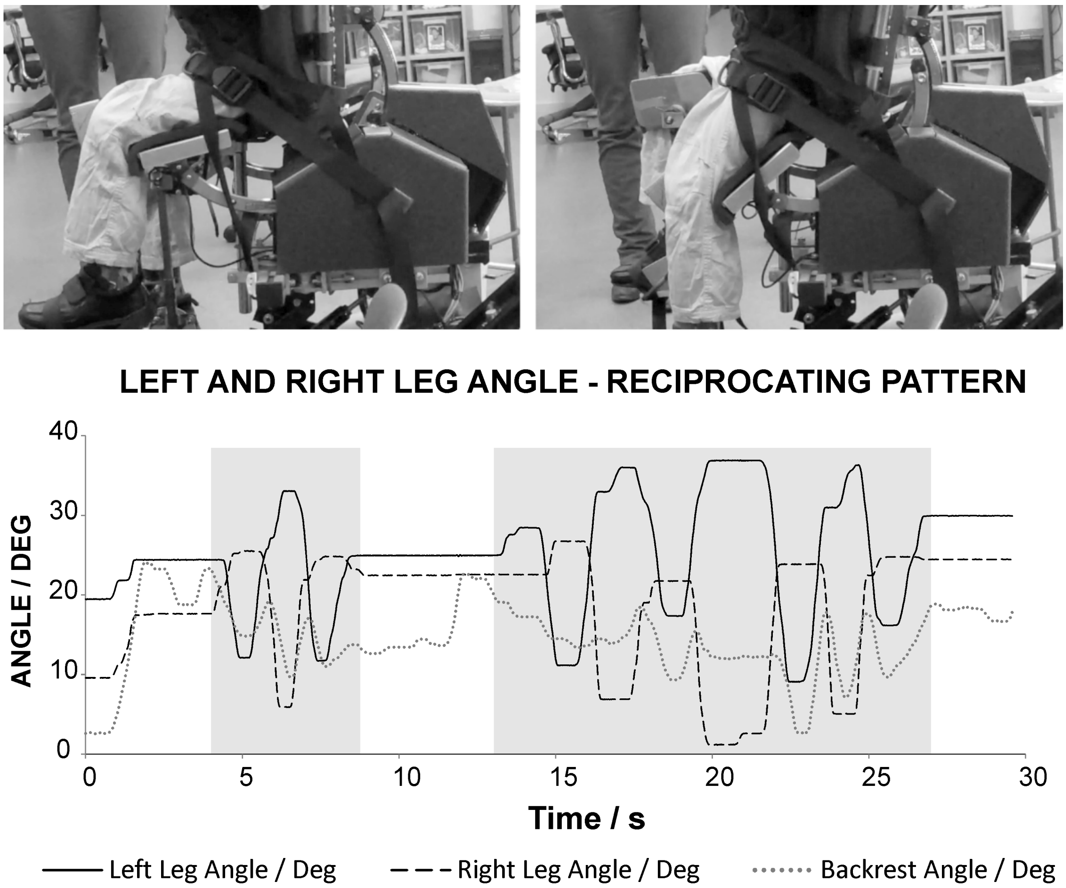

Figure 15-5: Two video stills and data from the sensors showing A1 during a reciprocating gait-like movement pattern. Asymmetric movements like these are not the result of his spasm pattern, but are most likely to be volitional. The two boxes on the data plot show the episodes of reciprocating movement.

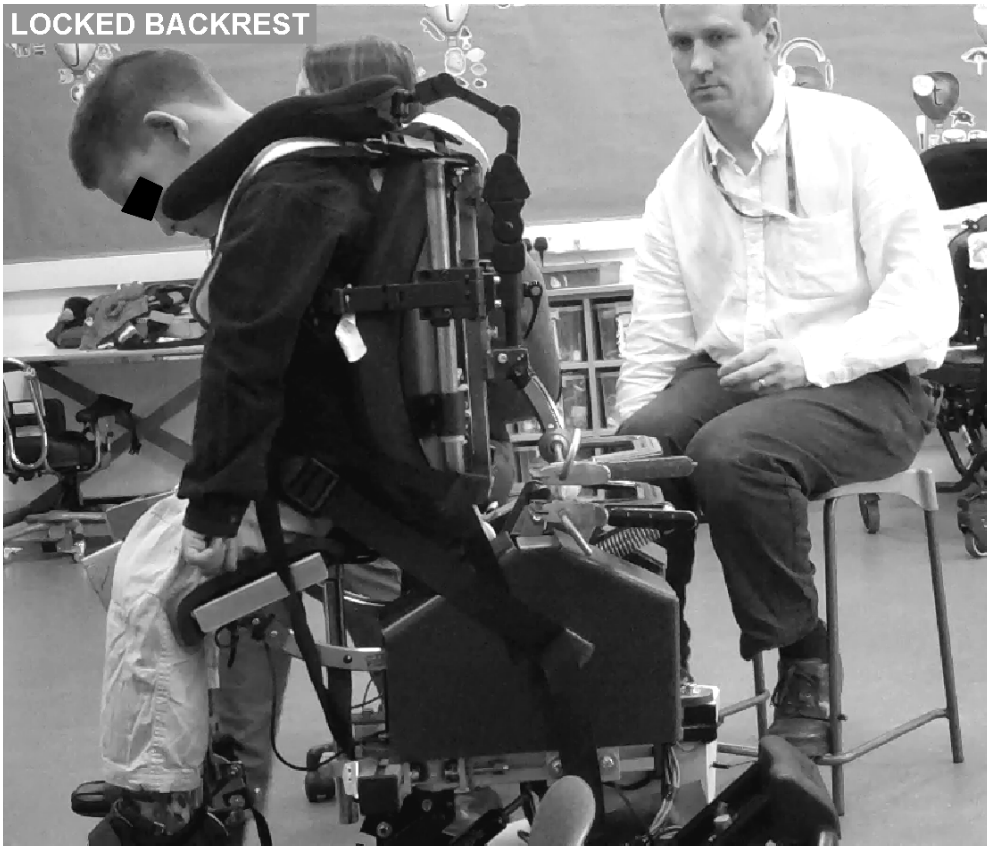

Figure 15-6: A video still of A1 sitting head down with the backrest locked on December 1st 2011. With the backrest locked, he maintained a head down position for a greater proportion of time (33%) compared with a free backrest (14%).

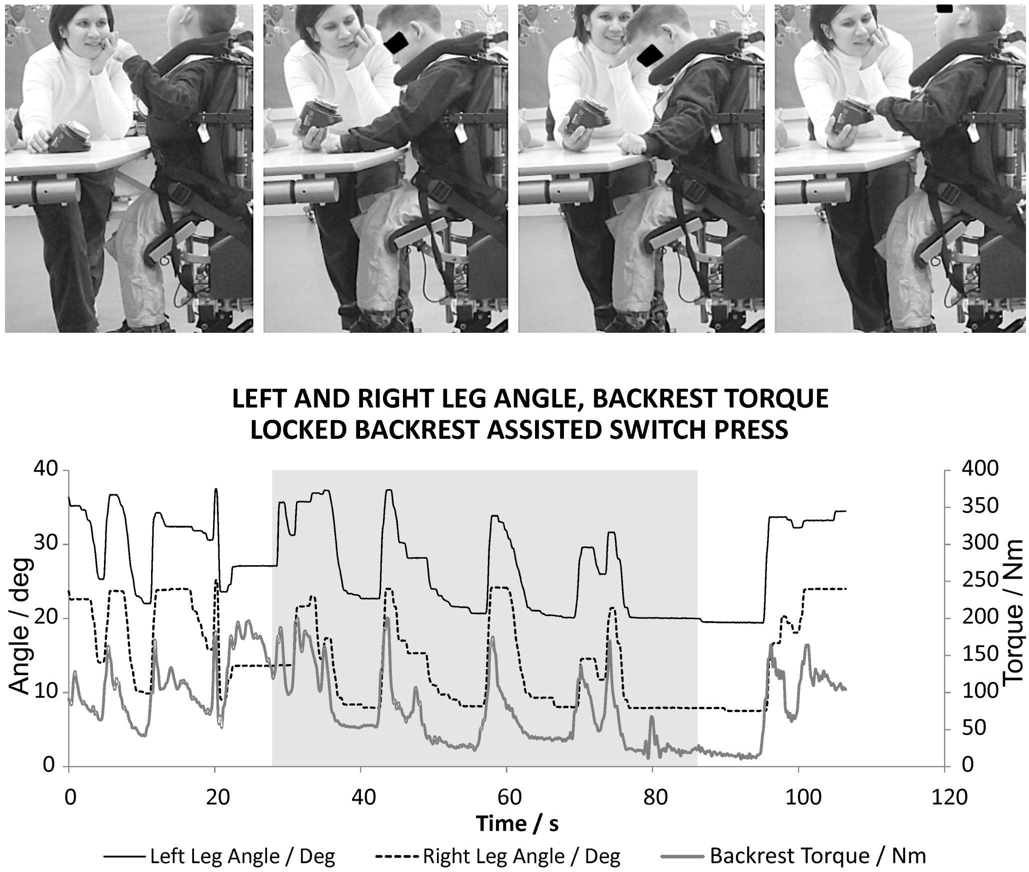

Figure 15-7: This sequence of photographs shows A1 attempting and eventually succeeding (with help) to press a switch held in front of him by his teacher. A1 used the table to provide support for himself: it improved his head control. The boxed data sample shows his movements from when the switch was introduced in this position until he pressed the switch. He was experiencing spasms throughout.

of his improved hand and upper limb function while in the dynamic seat. There was a stark contrast between his upper body control and mobility while in the dynamic seat, compared to his control and mobility while performing the same task in the static seat later in the day. Photographs and sensor data from the dynamic seat switch operation are shown in Figures 15-8 and 15-9 respectively. A1 was able to operate the large switch/voice recorder placed in front of him by utilizing controlled backrest movement. He also appeared not to be so 'fixed' by the symmetric and asymmetric tonic neck reflexes that immobilised his hands when in the static seat.

Comparing A1's ability to maintain an upright head position with the seat back lock and unlocked, his proportion of head-up time in the three minutes of time before unlocking the seat and with the table present was 90%. His proportion of head-up head time in the three minutes after the seat was unlocked and with the table present was 94%. This represents a reduction in head down time of 40%.

It is interesting to see the change in the quality of A1's movement when the backrest is unlocked. The data, shown in Figure 15-10, shows a clear transition point in all data channels - backrest and hips. A1's movements change from being smoother but generally higher torque (mean torque locked: 12.46Nm) and displacement, to being more complex and variable but with lower torque (mean torque free: 9.59Nm) and displacement. See Figure 15-11 for a frequency distribution of backrest torques before and after release.

Static Seat with table - No movement: After a break for lunch, A1 was positioned in his usual rigid classroom seat at a table. His seat was positioned with about 10° posterior tilt-in-space.

A1 was presented with the switch operated messaging unit that he had operate during the previous session, and was encouraged to operate it. Though he concentrated on the switch, looking at it and his hand frequently, he was unable to move his hand all the way to the switch. A series of video stills of A1 attempting to press the switch are shown in Figure 15-12. The research OT held the switch for him while he attempted to press it. He moved his hand away from the switch in a pattern similar to that which he used when in the dynamic seat, and then swept it forwards and towards his midline and the switch. When his hand came close to the switch, the drag of his hand on the table caused his hand to rotate inwards.

Two measurements were made of his head-up time:

1. The first period was the final three minutes (out of five) while A1 was attempting to operate the voice message player (02:00 to 05:00). This period included his best attempt. He was strongly engaged with this activity and with the research therapist who was doing it with him. He was vocal throughout. Head-up time was 90%.

2. The second period was three minutes while he was interacting with an animal noises merry-go-round (07:23 to 10:23). He was less engaged with this activity, but remained engaged with the therapist, especially when she suggested finding an alternative toy. Head up time was 86%.

Figure 15-13 is of A1 enjoying listening to a musical guitar toy. He was not distressed in his rigid seat. He enjoyed many forms of music, and would respond positively when he heard it, whether the music was part of his current activity or being played elsewhere in the classroom.

Figure 15-8: A series of video stills showing A1 pressing a switch activated voice message player. He used seat movement to assist with the switch press, and stabilised himself when doing so. The switch is indicated by an arrow. See Figure 15-9 for the data accompanying this movement.

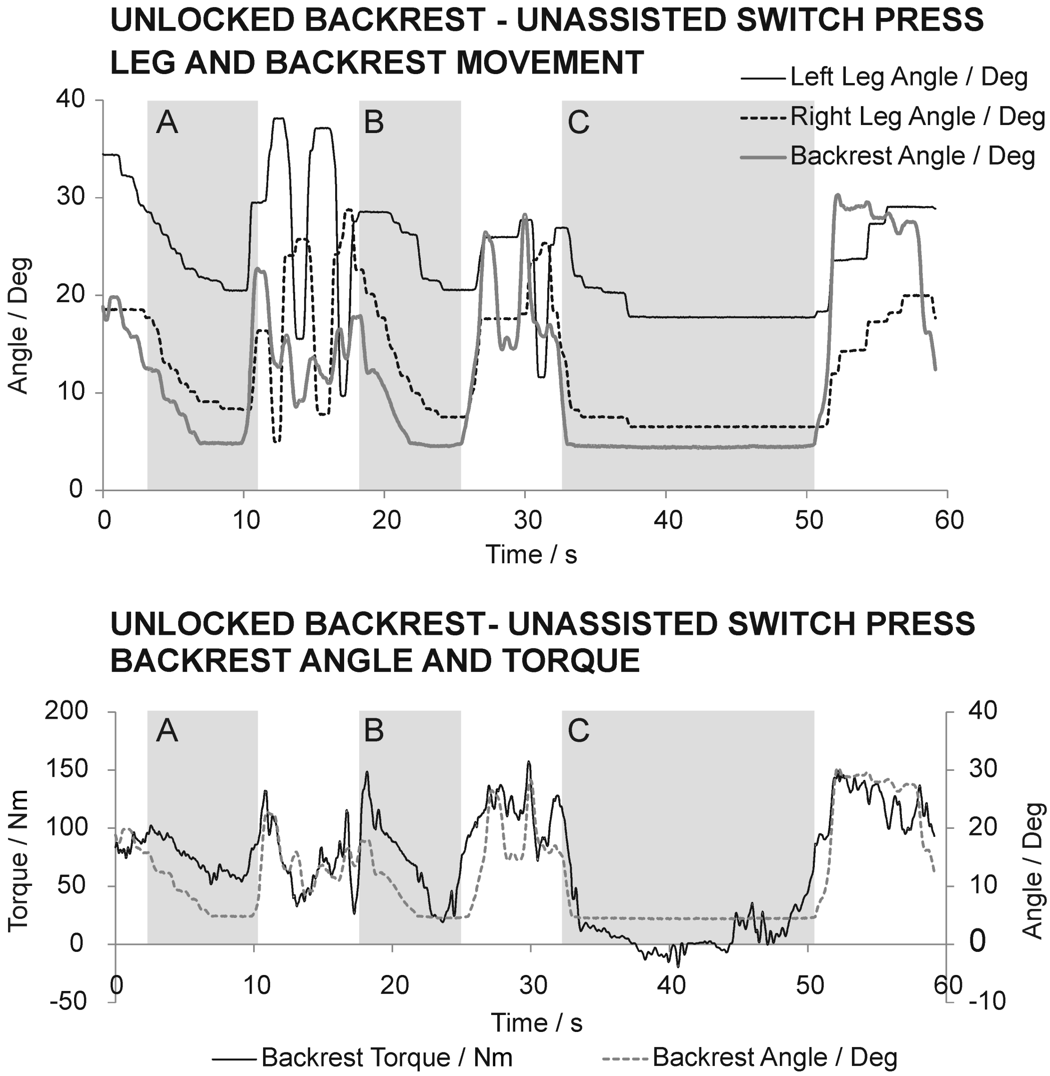

Figure 15-9: The sensor data boxes (A, B & C) show three attempts at pressing the switch. Each example shows a stable and gradual approach to the switch (with decreasing backrest angle and decreasing backrest force) and then a rapid release of control after pressing the switch. Box B shows the data from the image sequence above. A1 did not have this degree of control in his usual static seat.

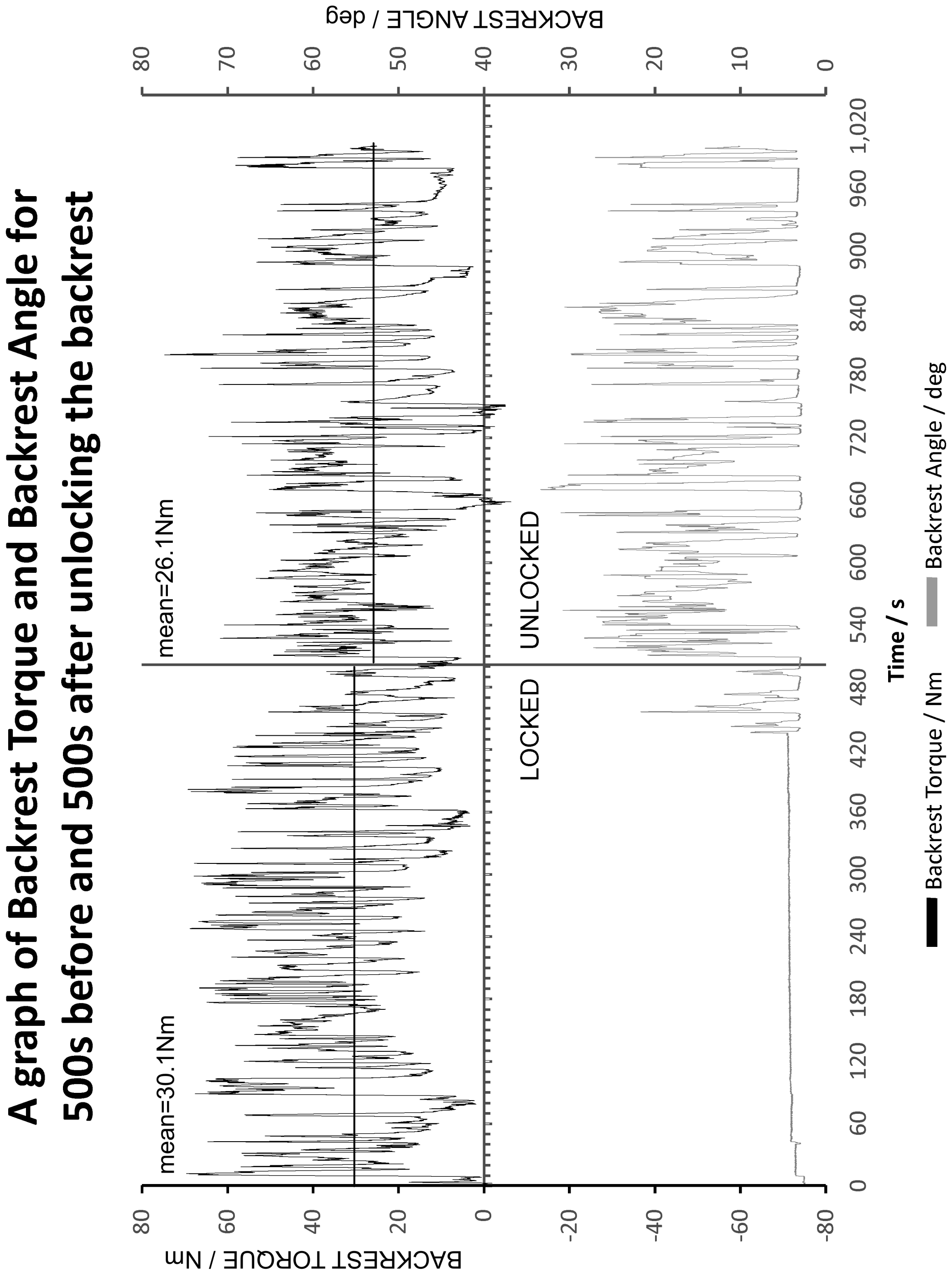

Figure 15-10: This is a graph of 500 seconds of data before and 500s of data after the seat back was unlocked; and shows the transition that occurs in the force data for the backrest. The peak backrest forces are reduced, and the character of the spasms has also altered.

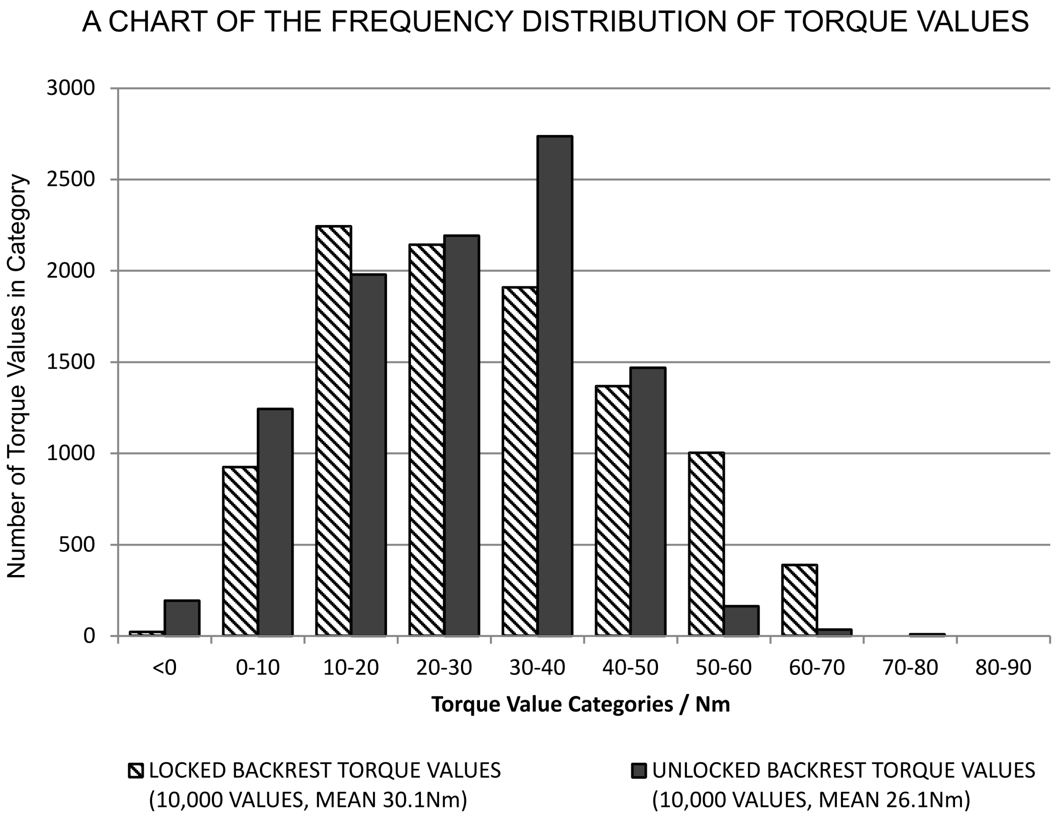

Figure 15-11: This chart shows the frequency distribution for 500s of backrest torque data before and after the backrest was released. With the backrest free, the peak torques are reduced, but there is a sharp increase in torques between 30Nm and 40Nm. Unlocking the backrest reduced the size of torque categories above 50Nm by 85%. This is a substantial moderation of A1's most powerful spasms. There are more negative torques with the free backrest, possibly indicating forward reaching, though these may also be the result of inertia in the backrest at the end of a forward movement when the it reaches its end stop.

Figure 15-12: A series of video stills of A1 attempting to operate a switch held by the research occupational therapist while sitting in his usual rigid seat. This was his best attempt, which took 33 seconds from when he moved his hand away from the switch at the end of his previous attempt until his closest approach to the switch. His previous attempts were also unsuccessful, often ending with his hand pressed against the table.

Figure 15-13: A video still of A1 enjoying listening to a musical guitar toy with the research engineer and occupational therapist. He enjoyed many forms of music, and would respond positively when he heard it, whether the music was part of his current activity or being played elsewhere in the classroom.

15.2.5 Conclusions

This evaluation was spent assessing the seat, rather than adapting it. It generated a very large quantity of data, and especially video data. The most useful data for the future design of the seat was the clinical observation of the research team and the therapists and classroom staff who know A1 well. As well as providing a record of interactions for subsequent analysis, the video data also provided a useful reminder of what occurred during the evaluations. A summary of the findings from the evaluation are given below:

Enjoyment: A1 enjoyed sitting in the seat, and was pleased to meet the research team. He giggled when sat in the new seat for the first time while he explored its movement, and was pleased to see the research team whenever they returned.

Comfort: The dynamic seat was comfortable and suitable for classroom use. There was no red marking on his skin after its use.

Head control: There were several factors that improved A1's ability to maintain an upright head position:

1. The addition of a table at elbow height in front of his seat, rather than no table.
2. Setting the dynamic seat backrest to be free to move rather than locked.

3. A1's level of interest in his activity appeared to affect his head-up time. He was able to maintain better head control when he needed to do so for an activity he was enjoying. He particularly enjoyed certain musical activities.

Spinal symmetry: A1's spinal symmetry improved while sitting in the dynamic seat, though his limb symmetry was better in his static seat. At the time of appointment A1 was noted to have a flexible spine with no significant concerns. A future concern raised was the development of a kyphosis (forward curve of the thoracic spine) due to low truncal tone and an inability to maintain an upright seated posture.

When sat in his static classroom chair, A1 appeared to be in a comfortable position with good head control. There was some rotation in his trunk in this seat, which could be a concern in the future. Sitting in the compliant seat A1 was more symmetrical, although his contact with the back rest was reduced. During observation the lack of contact with the back was acceptable, although this did fluctuate. Removing the dynamic aspect of the back did not seem to significantly improve his contact, however, it did reduce some of the functional gains of the compliant seat.

Spasm frequency: A1 experienced fewer spasms when sitting in the dynamic seat compared to when he was sitting in the static seat. The direct measurement of spasm frequency carried out by video analysis of portions of sitting time supported this finding, however the opinion of A1's school team was that he experienced more spasms in the dynamic seat. This discrepancy may be due to:

1. The difficulty with observing spasms in the constraining and enclosed static seat compared with the mobile and open dynamic seat.
2. The video used for the measurement was exceptional and not representative of A1's overall movement.
3. Volitional movements in the dynamic seat were misidentified as spasms.

Volitional movements: A1 was able to make voluntary movements in the dynamic seat which were impossible in the static seat. For example, he used a backwards seat movement to move his face away from a member of staff trying to clean his face, and used a forwards seat movement to assist with operating a switch on the table in front of him. He demonstrated good control of the seat position. He also frequently made gait-like reciprocating leg movements that were not part of his spasm pattern.

Hand function: A1's hand function improved in the dynamic seat. Improvements in hand function while using the dynamic seat were reported by A1's teacher during the evaluation. This was confirmed by the research team in 1st December 2011. The development of fine motor control in typically developing children relies upon a stable base of support and sufficient trunk control to allow the development of distal movement. The individual also needs to be able to make postural adaptations to suit activity requirements. For children with significant motor impairment, the stable base is provided by their specialist seating, which also supports their body proximally to facilitate distal movement. However static seating is unable to facilitate the postural adaptation during activity. Many children with neurological impairment also experience fluctuations in muscle tone, including an increase in tone immediately prior to and during volitional movement.

Observations of A1 using a switch in his static seat and the dynamic seat were as follows:

Static Seat	**Dynamic Seat**
Keeping hands forward on the table	Keeping hands forward on the table
When attempting to hit a switch, A1 was pushing up during a spasm, but was not able to use increased tone to help move his arm forward.	A1 was using whole body extension to facilitate volitional movement; pushing back with a whole body movement rather than isolated shoulder / arm movement which was less effective.

Hand function was best in the dynamic seat when it was fully unlocked and combined with the use of a table or tray to support his arms and hands.

Attention In order to access the school curriculum and interact with the environment, it is vital children are able to attend and maintain this attention for periods of time. A1's class teacher reported that his attention was better when using the dynamic seat, and that he seemed more active in his interaction with the environment and those around him.

Social engagement: A1's teacher reported that his social engagement improved in the dynamic seat, including an improved ability to vocalise on cue when in the dynamic seat, though his vocalisations were better controlled when he was sat flexed in his static seat. He also used movement to attract attention and to communicate. A1 was able to engage in a football activity while sitting near the floor in the seat, kicking a ball in front of him.

Manual handling: It was difficult to put A1 into and out of the seat. Hoisting was difficult because of the need to flex A1 to relax him enough to be able to put him in the seat. Easy-to-use locks on the leg support and backrest slides would improve this by providing a stable platform on which to rest his weight towards the end of the transfer.

Visual/Design Impact: Several parents commented positively on the design of the seat. His teacher reported that *"All they see is [A1's] expressiveness and his ability to move"*. One of the classroom staff described it as his *"bionic chair"*.

15.3 Transfers, manual handling and feeding.

Some concern was expressed by staff when this seat was introduced that it was too difficult to transfer children into and out of the seat without lifting. A followup session requested by the school therapists and was held at A1's school in July 2012 to a) determine a strategy for no-lift transfers using a hoist to lift him; and b) to look at the possibility of locking the leg supports in a flexed position during feeding.

15.3.1 Transfers

The session explored the use of two different sling designs for transfers into and out of the seat. The first sling was a conventional 'cup sling' from "Care and Independence" (See Figure) that supported him in a flexed position. A1 was placed on this sling and transferred into the seat while still sitting in the sling. He experienced several spasms while in the sling, and the team had to wait for these to fade and reposition him to increase his flexion before transferring him into the seat. The sling was detached from the hoist and left in the seat underneath A1. This sling was adequate for transfers, though not ideal. It did not provide adequate head support, which was provided by a member of the team. A1's leg abduction was increased, which helped to reduce his propensity to spasm.
Concern was expressed that A1 was not sitting in the seat so well with the sling in place. This was thought to be for two reasons:

1. He was not as flexed in the sling as he usually was when transferred by a lift, preventing his buttocks from being placed at the back of the weight bearing saddle against the seat back.
2. He was reclined in the sling and less upright than when transferred with a lift, which also impeded his correct placement on the weight bearing saddle.

A 'glove sling' was tried that supported A1 with thigh and chest supports. This sling did not provide any pelvic support but achieved weight bearing through his thighs. It did not achieve sufficient flexion to eliminate A1's spasms and transfer was not attempted.
A third larger cup sling was found and tried at the end of the day that provided more head support and flexed him to a similar degree to the first cup sling. Transfer into the seat was not attempted as time had run out and A1's needed to return home in his booked transport. His positioning in this sling was better than the other two, but it was too big and would not have worked well in the seat. He was also reclined in this sling.
In summary then, transfer to the dynamic seat was best effected with a conventional cup sling, but with the following adaptations:

- The slot between the legs would be extended further towards the crotch to improve the mobility of the legs and the ability of the sling to fit around the abduction plates on the thigh supports.
- The back of the sling would be extended to improve head support.
- The sling anchor points and webbing lengths would be adapted to create a more upright slung position for A1.
- The sling would be adapted to create a more flexed position for A1.

A meeting of A1, his teacher and therapy team, the research engineer and the sling manufacturer was arranged for September 2012 to determine a detailed specification for a new sling.

15.3.2 Feeding

A1's speech and language therapist was concerned that the tone in his head was too high while he was feeding, causing him to bite strongly on his spoon. She worked with A1's physiotherapist to find a strategy to reduce it. The speech and language therapist was aiming for a position such as one she had observed while A1's mother was feeding him on her lap, where he was flexed and sitting across one thigh with the other thigh supporting his sacrum.

Two short trials were carried out. The first trial was to lock the hip support so that A1 was fixed with a hip/trunk angle of 80° (100° of hip flexion) to reduce his tone. The seat could not be adjusted to allow this much flexion, so seating was tried with the leg supports locked at 90° to the backrest. This was not successful. A1 sat in the locked seat, but continued to experience spams and did not reduce his mandibular tone.

So that a more flexed position could be investigated, the team removed A1 from his seat and simulated his seated position on the physiotherapist's lap. A1's tone was assessed at various hip flexion angles, measured with a goniometer. It was found that at about 80° hip/trunk angle (100° hip flexion) his tone rapidly diminished. While this achieved the desired reduction in mandibular tone, he also lost head control and his head flopped forwards onto his chest. There was a boundary angle at about 100° of hip flexion where his whole body tone reduced. A1's teacher commented that she used head position as a reliable indicator of whole body tone.

It was decided not to provide a facility to lock the leg supports at 100° of hip flexion, but to continue with the seat with the adjustable rotation limiters already installed. These were to be redesigned to make them easier to use and adjust without the need for tools.

15.4 Post delivery report from A1's Class Teacher, London, 18th June 2012[8]

Six months after the end of the research, A1's class teacher reported back to the research team on his on-going use of the seat. Her report is quoted below:

> *"So firstly, things are going really well with the chair, with him spending the majority of his time in school in it. S&LT* [speech and language therapy] *have cleared him for eating in it, with just the back needing to be locked off, rather than the legs as well.*
>
> *There continues to be a slight rock in the chair when his legs are moving lots, dancing away, which those that feed him regularly were initially uneasy about. However, just pausing and waiting for him to be ready again works fine. He has his snack and lunch in the chair every day now.*
>
> *On occasion, especially initially, people were forgetting to release the back for him after he had finished eating. We noticed that very quickly he became incredibly uncomfortable, sweaty, agitated and upset. When the back was locked unnecessarily for 45 minutes or more he became very sensitive. We found that even after releasing the back he continued to be in discomfort, only managing to calm once he was taken out of the chair. Thankfully,*

that hasn't happened for a good few weeks now, and he is continuing to tolerate having the back locked off for the 45 minutes he eats for.

As the weeks have gone on and he is using the chair more, I have noticed that the people that work with him regularly are becoming more and more confident with using the chair. I will be honest, many of the team were completely daunted by it during the trial, because it is such a unique piece of equipment, and contradicts many 'principles' that are instilled, namely, strap them in and hold them as still as possible. Now though, the team are very comfortable with the chair, with more and more of them being happy to get him in and out of it.

We did notice soon after the chair returned to us in April that when different people put him in the chair, he was slouching ever so much, shoulders really forward with a significant reduction in his head control. He was also using the chair in the wrong way, pushing back and not using his legs at all. I think (though this is only my untrained and unverified opinion) that his hips were not straight and not all the way back into the chair. When I took him out of the chair and then put him back in myself, he returned to sitting up straight, using the dynamic function correctly and with his normal head control. I guess this just highlights the importance of making sure he is sitting in the chair correctly when he initially goes into it.

So there are a couple of small issues that we are having with the chair. While they are significant, we are managing fine to work around them.

The most noticeable is the tilt action present on the [bought-in] base itself. That doesn't seem to be holding (though nothing does with [manufacturer]*), so has needed re-adjusting a couple of times, preventing* [A1] *from literally lying down when he goes into extension. It's not something that I can easily adjust when he is in the chair, but its something I keep an eye on, tweaking after school every couple of weeks.*

There is a small amount of movement in the backrest when it is locked off. While the part that you added to lock the back works wonderfully, the blue plastic covering over the moving parts on the back of the chair prevents the lock from going all the way down to the solid, non-moving red metal at the bottom, where I presume you intended it to rest on. It means that the movement in the plastic and the small amount of allowance on the curved metal arm at the back (I'm sure you have a much more impressive name for it) allows for a small amount of movement in the back rest. [A1] *doesn't really try to use the back rest anymore when he knows he is eating, but sometimes, if he is especially excited/happy, then it can slow lunch down.*

[a section on a technical fault on the bought-in base was removed for brevity]

Aside from that, there are just very minor, and very common issues that occur with chairs. Namely, the headrest loosening every so often, and the footplates being a little too low when he doesn't have his AFOs and specific splint shoes on."

Chapter 16

The nature of whole body extensor spasms

This short chapter describes the nature of the whole body extensor spams experienced by the children in this study.

In addition to designing technology to support children with whole body extensor spasms, through the evaluation of instrumented dynamic seats, this research has also collected a large quantity of qualitative and quantitative data on the nature of whole body spasms. One further paper and a conference abstract were found during the research programme that provide some limited insight into the characteristics of whole body extensor spasms[1, 59]. The spasms are complex and not well understood neurologically: the literature search did not yield any papers specifically describing the origins or causes of such spasms beyond attributing them to damage to the motor control regions of the brain. There is a body of neurological research into reflexive extensor movements of the lower limbs ([60, 61] for example) which provides some insight into possible mechanisms for the generation of extensor spasms, however it does not address the characteristics of whole body extensor spasms. There is a need for the integration of neuroscience, therapy and rehabilitation engineering in this context as until spasms and their origins are better understood, design of seating for children with these complex needs will be led by the evolution of seating through empirical means, rather than by design to specifically address the causes of spasms.

The characteristics of whole body extensor spasms are described below:

Magnitude: The magnitude of the measured torque at the peak of a spasm is highly variable. For example in the data shown in Figure 15-10 from the final evaluation of the second seat, the peak backrest torque varies from 31Nm to 75Nm.

Time domain: Spasms also can vary considerably in their frequency and duration. In this respect Child A1 and Child R1 were very different. R1's spasms were usually very regular with about 1.75s between spasms. Looking at two samples of twelve spasms from settled regions either side of unlocking of the data from the final evaluation (see Figure 15-10), the time period for 12 spasms varies between 3.25s and 31s (mean 11.4s, standard deviation 6.6). See Figures C-1 and f.bigsample2 in the appendix for the complete backrest data set from this evaluation.

Triggers: Spasms usually, (though not always) initiate in response to a variety of stimuli: tactile stimuli, such as pressure on the head or sole of the foot; emotional stimuli, such as excitement or distress; and environmental stimuli, such as a sudden loud noise, a sudden movement, or a change in lighting. These factors also lead to spasm intensification, and are additive. For example, a distressed child, or a child in a noisy environment will be more sensitive to tactile stimuli.
Other environmental, physical, and emotional factors suppress spasm initiation, if not eliminate it entirely: large flexion of the hips ($> 100°$) inhibit spasms and cause a general reduction in tone sufficient to cause the child to lose head control; a quiet unstimulating environment calms the child and reduces spasm trigger sensitivity; and emotional security provided by the presence of a calm parent reduces anxiety, also reducing spasm trigger sensitivity.

Spasm Profile: The profile of spasms is also variable, depending upon the child and the circumstances. Examples of regular periodic spasm torque profiles are shown in Figure 16-3. These spasms were high frequency and powerful, and R1 could sustain this movement pattern for ten minutes before it became necessary to remove him from the seat due to his becoming tired.
R1's spasm pattern did not always follow this form in Figure 16-3. On occasions he experienced longer spasms interposed between his regular pattern. See Figure 16-2.
Finally in this chapter, Figure 16-3 shows an interesting and widely occurring (though not universal) feature. This figure shows data from R1's evaluation of the first independent seat in January 2011. It can be seen that his spasm torques reduce when the preload on the spring is overcome and movement begins. This feature is evident in the backrest and leg support movement.
A1's spasm pattern was far less regular than that of R1. Figure 16-4 shows two samples from 26th November 2010 data when A1 evaluated the first independent seat.
The 26th November 2010 data from A1 in Figure 16-5 shows a similar feature to R1's data in Figure 16-3 where the rate of increase of spasm force reduces when the backrest movement begins. See Section 11.4 for a description of this evaluation.

A GRAPH OF PERIODIC HIP AND BACKREST TORQUES FOR R1, JANUARY 2011

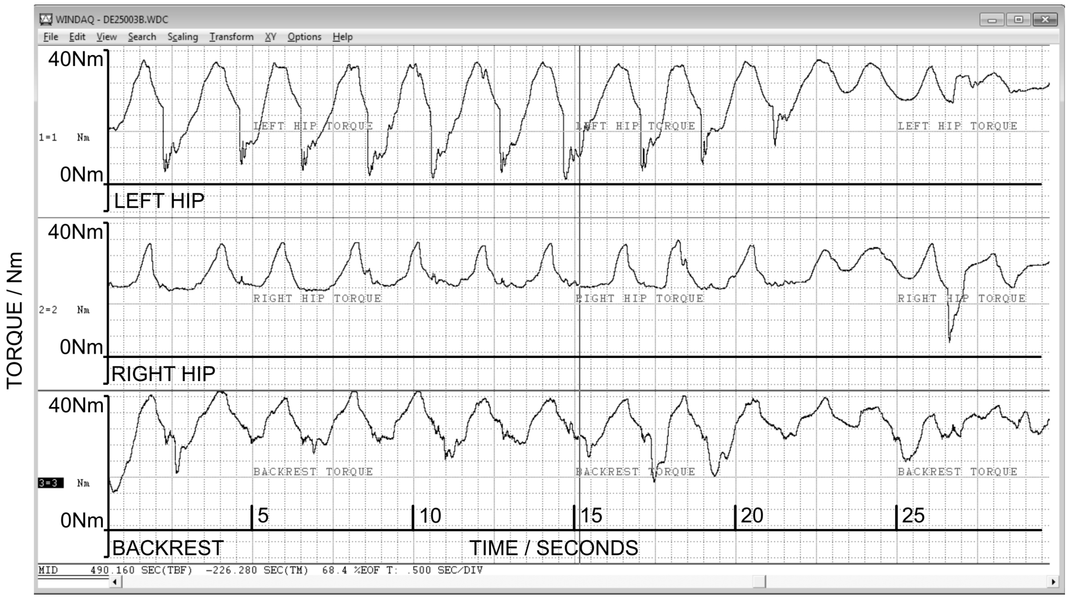

Figure 16-1: A graph of regular high frequency alternating flexor/extensor spasms measured from R1 in the first independent seat on 11th January 2011. He could maintain these spasms for many minutes, becoming very tired. It is interesting to note the small high frequency oscillation at the beginning of each spasm. This may be the spasm initiating or alternatively a mechanical oscillation resulting from the change in direction of the spring mechanism. If it is a spasm feature, then it is possible that it could be used in the future as a trigger for reconfiguring an active dynamic seat to behave differently during a spasm compared to its behaviour during functional non-spasmodic use.

A GRAPH OF PERIODIC AND NON-PERIODIC HIP AND BACKREST TORQUES FOR R1, JANUARY 2011

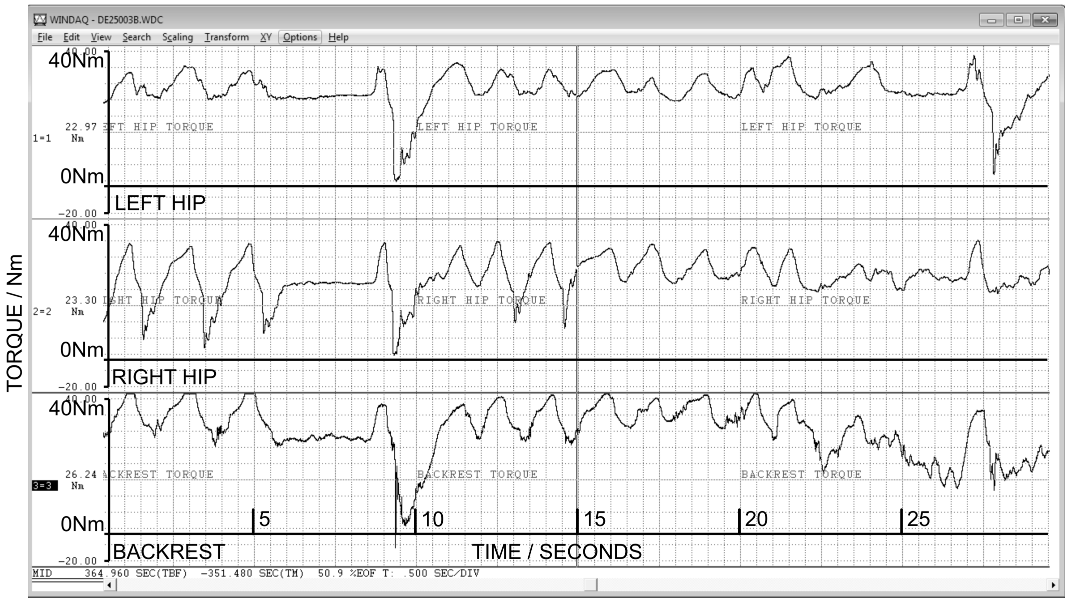

Figure 16-2: This data, also from R1 on January 11th 2011, shows two longer spasms interposed within R1's more typical 0.6Hz pattern. This data also illustrates the offset of the spasm torques above the baseline. R1 is applying a continuous torque, with the spasm oscillations evident on top.

GRAPHS OF TORQUES AND SEGMENT ANGLES FROM R1, 11TH JANUARY 2011

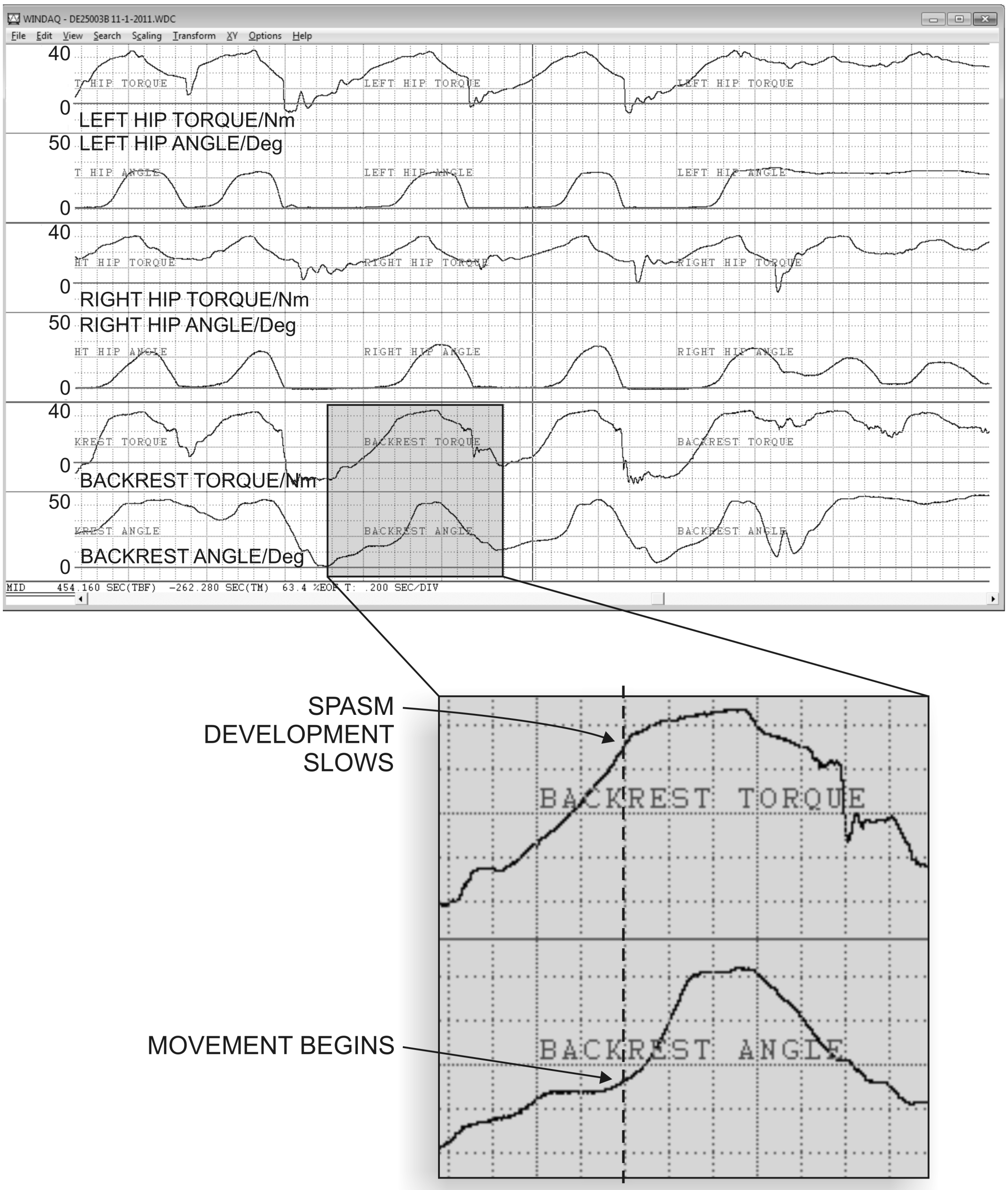

Figure 16-3: This torque and movement data from R1 in January 2011 shows spasm profiles in detail. The box shows where the rate of increase of spasm torque reduces as the seat backrest starts to move. This feature is widespread throughout R1's spasm data, and suggests that it is when movement begins and the spasm is no longer positionally resisted that the muscle activation reduces.

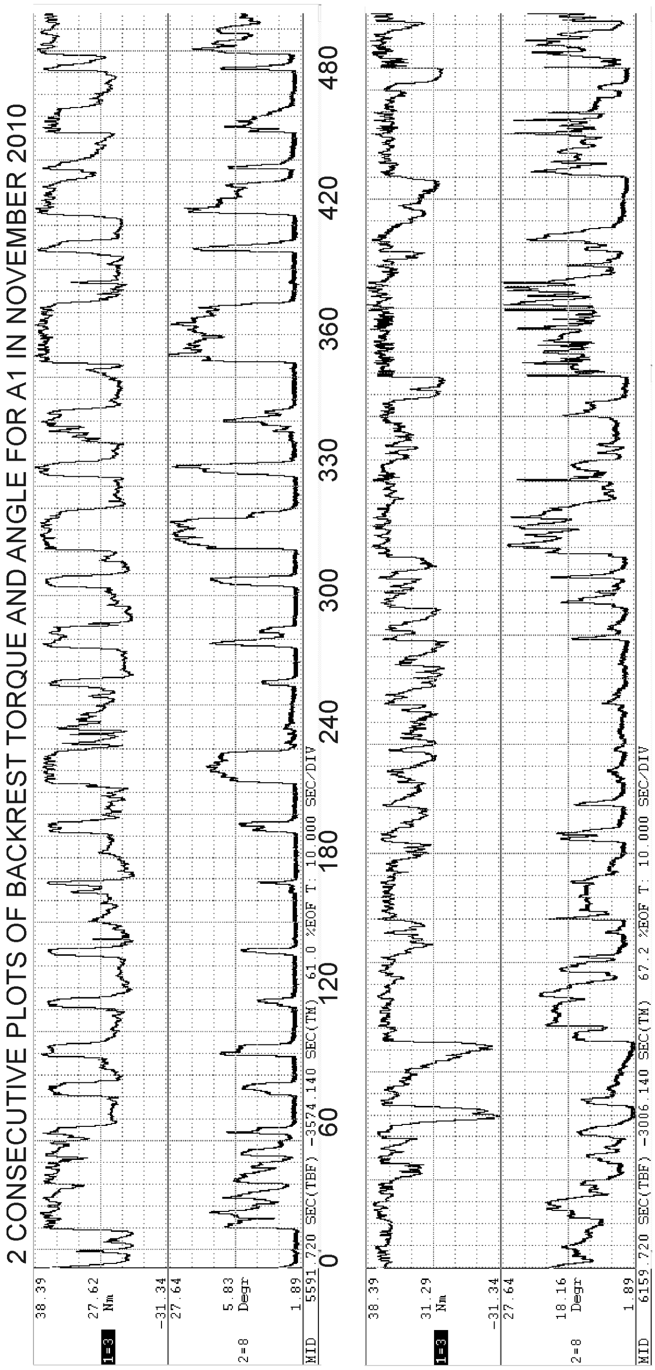

Figure 16-4: Two samples of data from A1's evaluation of the first independent seat in November 2010. These two consecutive samples demonstrate the variability of A1's spasms.

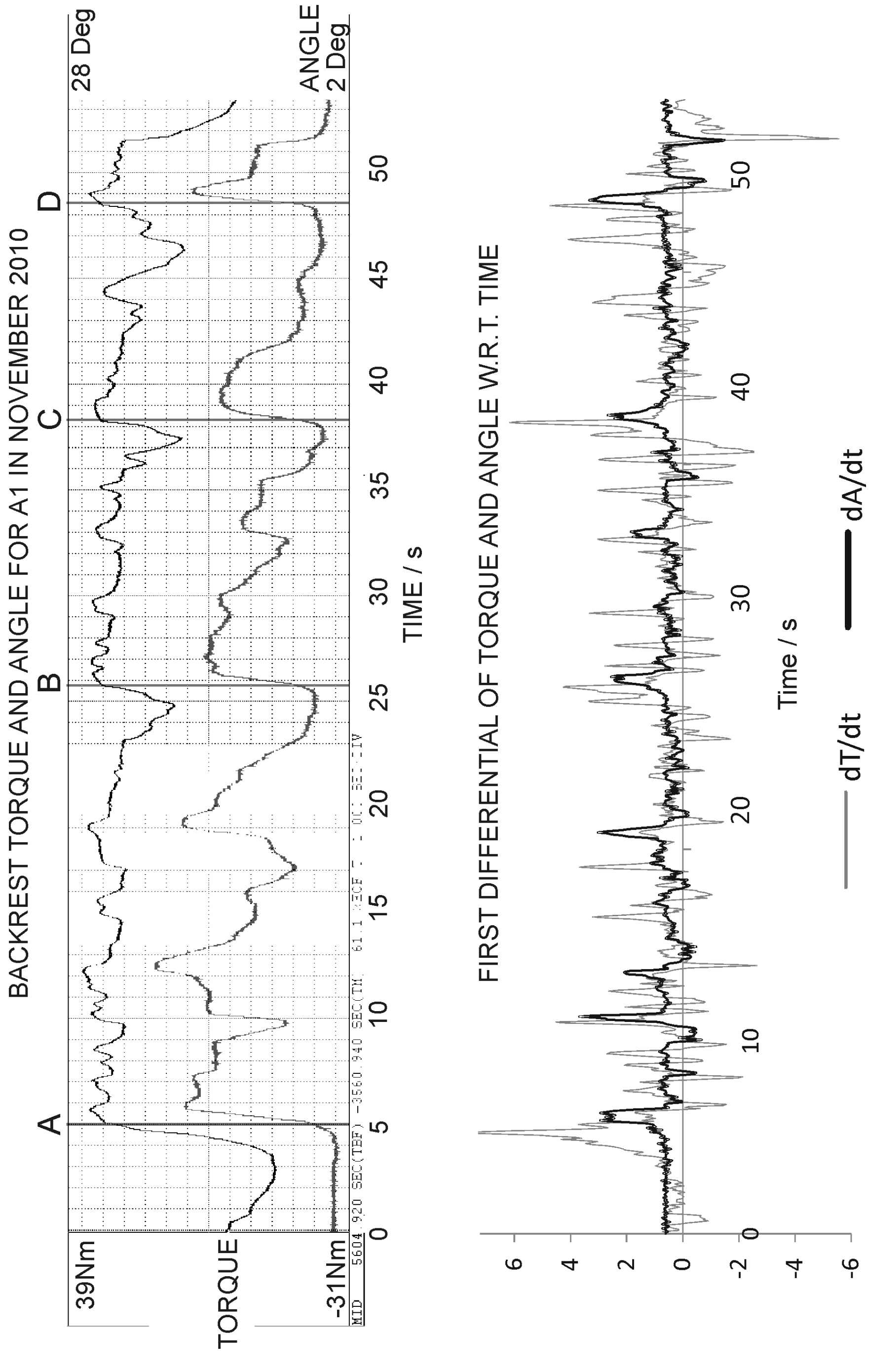

Figure 16-5: TOP: A graph of backrest torque against time for A1 on 26-11-2010 while using the first independent seat. The points in time indicated by the lines at A, B, C and D show a reduction in the rate of spasm torque increase as the the seat backrest begins to move. BTM: A graph of the first differential of the data in the graph above showing how the Torque increase rate reduces as the Angle increase rate increases.

Part V

Discussion and Conclusions

Chapter 17

Discussion

This chapter discusses the outcomes of all three phases of the research and identifies the conclusions that can be drawn. Firstly though, the work completed is reviewed.

17.1 Summary of the research

17.1.1 Referral from Great Ormond Street

The research began with a referral to BIME from Great Ormond Street Hospital in 2006 for comfortable seating for a child with dystonic cerebral palsy and whole body extensor spasms. A dynamic seat was designed for this child that incorporated:

1. A dynamic backrest, that was hinged under the seat platform, below the hips;
2. Dynamic footrests, that were hinged coaxially with the knee joints, and linked to the backrest.
3. A saddle seat that abducted the child's hips.

Evaluation of the seat showed that dynamic seating could provide comfortable seating for children with whole body extensor spasms. The evaluation also suggested that children with severe dystonic cerebral palsy could learn to control such as seat.

17.1.2 Generic seat design - linked seating

A programme of work to design a generic seat for children with whole body extensor spasms was begun in August 2008, and the first seat was designed to deepen understanding of extensor spasms and how a child experiencing them might be seated in comfort. This first prototype was unsuccessful in that it was not useable for any prolonged period by the first child recruited to the research. Child R1 exhibited rapid alternating extensor/flexor spasms, and easily became anxious and distressed.
This failure resulted in a re-evaluation of the assumptions made in the project about the design of seating, and a return to the first principles of how support might be provided for a child with whole

body spasms. An April 2009 evaluation of seating concepts at A1's home, and observation of how his mother held him yielded a novel concept for the dynamic seating of children.

17.1.3 Independent dynamic seating feasibility study

The new concept (Section 14.2) prioritised movement of the legs over movement of the back and head, with the aim of functionally stabilising the head and hands.
A new prototyping method was developed (Chapter 4) that enabled dynamic seating concepts to be evaluated without the time and cost required for building complex prototypes. Soft prototypes (Spring/Summer 2009) and semi-soft prototypes (Autumn 2009) of the new concept were evaluated with two children and found to be able to provide comfortable seating. This feasibility study provided sufficient confidence for design of a fully functional dynamic seat to start in January 2010.
During this study, Child A1 was recruited to the research programme. He was very different to Child R1: his spasms were much slower and more powerful; they were (at that time) more asymmetric; and he was less anxious.

17.1.4 Fully independent dynamic seat design and evaluation

Having completed the feasibility study, a fully independent dynamic seat was designed that provided for independent movement of the child's legs and back while seated (Chapter 10). It was evaluated with two children - R1 and A1. During the design phase, R1 experienced a major and prolonged seizure. This almost eliminated his spasm pattern and he no longer met the project inclusion criteria. However contact with his family and school was maintained. Sadly, however, his spasms returned a few months later, and he rejoined the project following a surprisingly successful assessment at Great Ormond Street Hospital in December 2010 (Section 11.4).
The November 2010 evaluation with A1 progressed well (Section 11.4). He sat in the seat for prolonged periods of time. The need to move the back rest centre of rotation was confirmed. A1 was reported to show functional gains when sitting in this seat. The most major modification identified was that the backrest centre of rotation needed to be through the child's hip joint, not through an axis behind the hip joint as in this prototype seat.
The January 2011 evaluation with R1 (Section 11.4) was difficult, and configuring the seat such that he could sit in it comfortably took most of the week. However, at the end of the week, he was able to sit in the seat for a substantial proportion of a classroom session. Much was learned about the design of the seat, and significant modifications were identified. A significant change was the moving forwards of the anchor point for the pelvic strap. The need to move the backrest centre of rotation to the hip joint was confirmed.

17.1.5 Consolidated independent dynamic seat design and evaluation

The findings from the first independent seat were consolidated in a second independent seat design (Chapter 14) that aimed to move the design towards a more useable seat for the classroom. The aesthetic design of the seat was also considered at the beginning of this design phase, and a product concept was developed. The major differences between this seat and the previous design were that the thigh and backrest pivots were co-axial with the child's hip joint centre of rotation, and the pivots were implemented with a virtual hinge mechanism based upon segments of circular slide system. The virtual hinge enabled the seat to be more compact, considerably reduced its visual impact, and made it easier to transfer a child into and out of the seat.

Before this seat could be evaluated (September 2011), Child R1 withdrew from the project as his status had changed yet again and he was no longer eligible to participate.

The seat was evaluated in October to December 2011 for six weeks by Child A1 in his school classroom (Chapter 15). He used the seat for several hours each day. During the evaluation, his class teacher observed gains in hand function, and these were investigated further in the final evaluation session at the end of the evaluation period, where A1's movements and sitting in his usual static seat and the dynamic seat were compared. It was found that his hand function in the dynamic seat was improved.

The seat was returned to BIME in December 2011 for modifications after the evaluation, including the addition of locking mechanisms for the legs and backrest; and was delivered back to A1's school in April 2012, after which A1 regularly used the seat in his classroom for many different activities, including feeding. His class teacher reported that the seat worked well, and that he complained if he was sat in alternative seating or if the dynamic mechanism was locked (Section 15.4).

17.2 Research conclusions and discussion

This section discusses the findings of the research pertaining to: a) the nature of extensor spasms; b) the design of a *comfortable* seat for children with whole body extensor spasms; and c) a *functional* seat for children with whole body extensor spasms. Designing a functional seat became a secondary aim of the research, as the initial aim of a comfortable seat was substantially achieved. It is these functional gains that are of most interest for further research.

17.2.1 Designing a comfortable seat

The primary aim of this research was to design a seat that provides comfortable and safe seating for children with whole body extensor spasms. Initially the aim was far from being achieved, with distress being caused to the participating children. However, having devised and conducted the soft and semi-soft evaluations, they suggested that a comfortable seat was achievable and the project continued with this aim firmly in view.

Comfort was measured by observing the participants' reactions to the seat. Judgements made were guided by their school staff and parents, who knew them well, and understood their vocalisations, gestures and facial expressions. Cimolin[2] measured comfort with a numerical sensor based approach using movement and pressure analysis, however comfort is a subjective experience, as is pain; and it is the child's comfort that is the objective. Cimolin observed a significant reduction in the force applied to the seat back (mean value in static configuration 78.73 ± 19.97 N; mean value in dynamic configuration: 33.85 ± 1.77 N). A proportionally smaller reduction in torque (not force) was observed with the whole body dynamic seat when comparing the locked and unlocked backrest, however the leg supports remained free to move during both of these configurations so the 'backrest locked' seat was not entirely a static seat.

While pressure sensing was not used in this work, children were checked for redness on their skin indicating excessive pressure. All seats performed well in the buttock area. The main problems were encountered on the Anterior Superior Iliac Spines with the first independent seat, and were caused by pelvic strap pressure. This problem was resolved in the second independent seat by moving the backrest rotation axis to be coaxial with the hip, and by moving the pelvic strap anchor point forwards. Some problems were encountered on the inner thighs caused by pressure from the abduction plates on the first and second independent seats, but these were resolved with positional adjustment and minor remodelling of the plates.

Comfort and reaction forces

The evaluation work showed that a major contributor to discomfort in the seating for children with extensor spasms are the pelvic strap forces and in particular pressure from the strap on the Anterior Superior Iliac Spines (ASIS), aside from large internal forces and muscle contractions created within the child which are also likely to cause discomfort.

When a spasm occurs in a static seat, there is a large upward force generated mostly by the hip/spinal extension torque but also by foot plantar flexion and knee extension torques, that is substantially counteracted by the pelvic strap. If the pelvic strap is anchored behind the child, and no other downward vertical reaction is possible (such as through the top of a four point harness), then the tension in the pelvic strap will be much larger than the upward force as its vertical component will be small compared to its horizontal component. Additionally most of this reaction is an upward anti-gravity force that displaces the child's pelvis from the seat base, reducing pelvic stability.

In the prototype whole body dynamic seat, there are three effects that modify this situation:

1. The action of the knee joint torque is neutralised as the joint is unopposed and able to move freely, thus the knee torques no longer contribute to the pelvic strap reaction.

2. The direction of application of peak spasm forces is different compared to those in a static 90° Hip/90° Knee seat. Because the child is extended under peak force conditions, the main components of the reaction forces are horizontal and forwards. They are opposed by the horizontal component of the pelvic strap and the four point harness or chest strap. There is a much reduced vertical upward reaction; the anti-gravity reaction is substantially reduced, and therefore pelvic stability on the weight bearing saddle is improved. Pelvic stability is strongly linked with function[29]. It may be that the functional gains seen in this work are partly the result of more consistent contact and support from the weight bearing saddle.

3. The spasm intensity is reduced because the spasms are not opposed with hard stops, but are allowed to take their course. This reduces the torques applied to the whole system, improving comfort and stability.

Child A1, who evaluated two prototype seats for extended periods preferred them to either his static seat or his transport buggy. He showed a strongly positive emotional reaction to the beginning of evaluation sessions with smiling and giggling while looking at the seat; and a negative reaction with no smile and a frowning face on being told he was transferring to his static seat or his transport buggy.
The final prototype seat (the second independent seat - Chapter 14) was comfortable for Child A1 who evaluated it for extended periods in his classroom (Chapter 15). He used the dynamic seat in preference to his static seat since it was delivered for permanent use in April 2012. When transferred to static seating for feeding, he has strongly objected, and has become hot, sweaty and distressed[8]. Conversely, when discovering that he would be sitting in the dynamic seat for a session at his summer holiday club at school, he grinned at the staff who explained this to him, indicating with eye-gaze that the seat was the reason for his delight.
This thesis describes the design of a new dynamic seat for children with dystonic cerebral palsy and whole body extensor spasms that has been shown to be comfortable during sustained use for its evaluator A1, it being preferred by him to his usual static seating. Earlier iterations of the design were also assessed to be comfortable for their users T1, R1, J1 and A1.

17.2.2 Designing a functional seat

As the research progressed, it became clear that the approach being taken offered the possibility of functional gains by children using this new design of dynamic seat, compared to the same children using their usual static seating. Other research[7, 4, 2] with less disabled children suggested that functional gains were possible.
Hahn et al[4] measured function with the Gross Motor Function Measure (GMFM-66)[62, 63] and the Paediatric Evaluation of Disability Inventory (PEDI)[64, 65], but showed only small significant changes in function. However, Hahn briefly notes substantial changes in communication to and from the participating children that were anecdotally reported by parents:

> *"The PEDI measurements revealed more consistent improvement in the experimental group. Our results indicated improvements in the categories of Self-Care, Mobility and Social Function for both groups. However it is apparent that the experimental group experienced greater improvements in Self-Care and Social Function. Informally, many parents of the children in the dynamic [experimental] group mentioned that their child began interacting more with siblings, peers, and adult caregivers once they became familiar with the new dynamic system"*

[4]Pages 28,29

Cimolin et al[2] measured function with numerical parameters derived from sensor data. They did not publish qualitative findings in this paper, but did note that the participants' movements were smoother (lower jerk index) and of lower intensity when the dynamic mechanism was operating.
GMFM and PEDI were not used to evaluate the prototype seat as concern was expressed by the lead occupational therapist that they would not be sensitive to likely changes in the severely disabled children recruited to the project. Instead this work took a qualitative approach to measuring function,

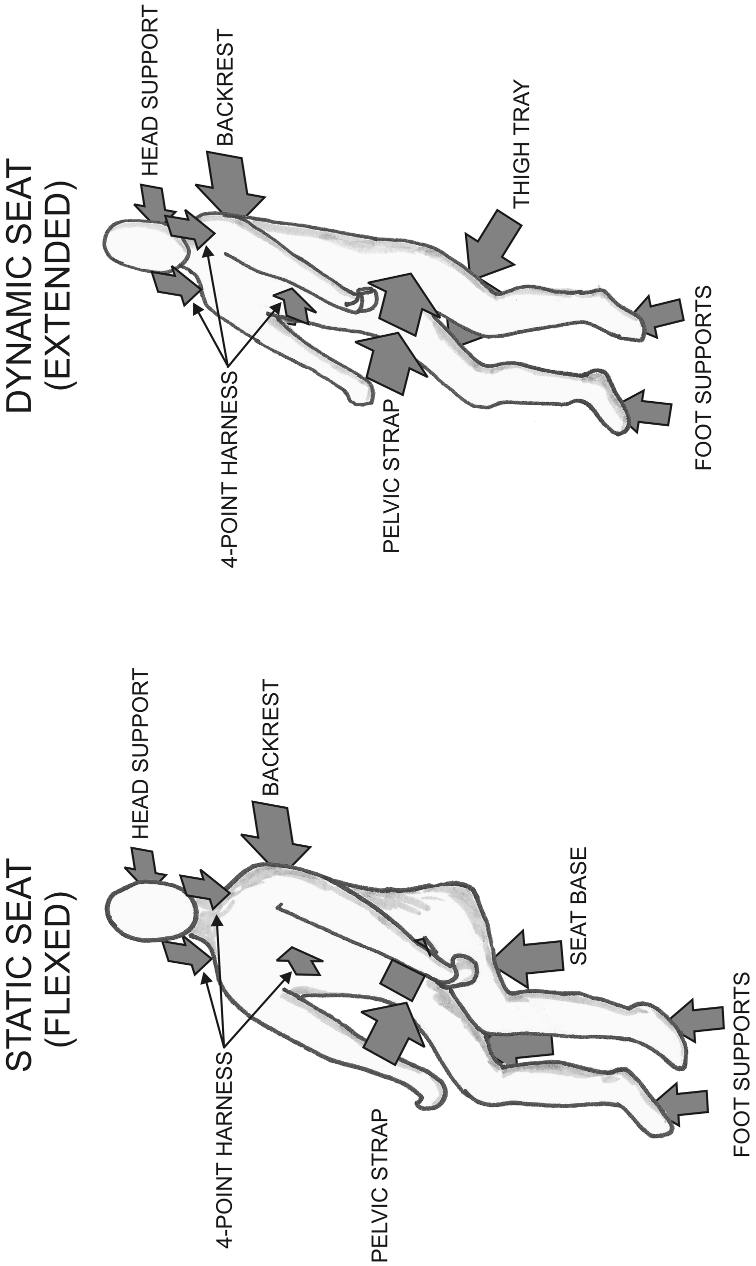

Figure 17-1: Two free body diagrams of a child sitting in static (LEFT) and dynamic (RIGHT) seats during an extensor spasm. This diagram shows the reaction forces generated by the joint torques, and why the pelvic strap forces can be so large. In the static seat diagram there is a large upward component of force generated by the seat base and foot rest reactions, generated by the foot, knee, hip and spine extensions. If the pelvic strap opposes these forces alone, without any additional constraint such as a four point harness, then the entire reaction is opposed by the pelvic strap at a mechanical disadvantage, further increasing the tension in the strap and pressure on the child's ASISs. In the dynamic seat, the reaction forces are reduced because the applied torques are lower and the knee torques are neutralised. See Section 17.2.1.

directly observing the children and noting the observations of the staff working with the R1 and A1. In the case of A1, he was directly observed and video recorded during functional interactions with the research team and a series of props while using the dynamic seat in semi-rigid and dynamic configuration; and also while in his rigid usual seating. These interactions are compared in Section 15.2.4.

The use of the new dynamic seat led to improvements in social and physical function. Improvement in hand function was reported anecdotally by A1's 2009/10 teacher during the long evaluation of the first independent seat (Chapter 11). During the evaluation of the second independent seat (Chapter 15), A1 was reported to be interacting more with his peers and staff both physically through movement and also vocally. His 2011/12 teacher also reported that his hand function had improved during this second long term evaluation. This observation was followed up with a small series of hand function tests carried out by the research team during the final evaluation session, described in Subsection 15.2.4. In this evaluation there was a clear functional gain when he was using the dynamic seat, and also an observed improvement in the quality of A1's movement, which seemed to be less 'locked', smoother and more controlled.

The results from this work suggest that the use of the dynamic seat, and the children's ability to learn how to use the movement it affords them, contributed to their increased ability to communicate and attract attention both vocally and with gesture. **When seated in dynamic seating, some children with severe neurodisability are able to learn additional postural control and utilize that control to improve their classroom functioning within a period of a few weeks.** This learning occurred in children well past the 'golden window' for neuromotor development between birth and approximately age two years when most motor learning occurs[36, 34, 38, 66]. It is possible that infants with neuromotor disability may make long-term improvements in motor function and postural and fine motor control through experimentation with movement in functional dynamic support systems[36]; and that children may be able to 'problem-solve' their own disability to some degree as they are provided with a sustained and consistent context for experimentation with functional movement. This possibility, highlighted by the learning seen in this research, is an important area for further research. The work of De Graaf-Peters[36], Warren[28] and McEwen[12, 13] suggests that children with cerebral palsy learn postural control through experimentation with movement, and that they are able to exploit that control to gain function in physical and social domains. The new Whole Body Dynamic Seat offers an opportunity for experimentation with functional movement and postural control to severely disabled children with cerebral palsy. Observations made during this research of children with severe cerebral palsy learning to control their posture while in the new dynamic seat (Chapters 15 and 6) support the hypothesis that:

"Children with severe cerebral palsy and whole body extensor spasms are able to develop functional motor control strategies through functionally motivated experimentation with movement while using whole body dynamic seating."

17.2.3 Seating and whole body extensor spasms

In addition to designing technology to support children with whole body extensor spasms, through the evaluation of instrumented dynamic seats, this research has also collected a large quantity of qualitative and quantitative data on the nature of whole body spasms. One further paper and a conference abstract were found during the research programme that provide some limited insight into the characteristics of whole body extensor spasms[1, 59]. Extensor spasms are complex and not well understood neurologically: the literature search did not yield any papers specifically describing the origins or causes of such spasms beyond attributing them to damage to the motor control regions of the brain. There is a body of neurological research into reflexive extensor movements of the lower limbs ([60, 61] for example) which provides some insight into possible mechanisms for the generation of extensor spasms (a lack of cortical suppression of reflexes?), however it does not directly address the characteristics of whole body extensor spasms.

There is a need for the integration of neuroscience, therapy and rehabilitation engineering in this context as until spasms and their origins are better understood, design of seating for children with these complex needs will be led by the evolution of seating through empirical means, rather than by design to specifically address the causes of spasms. For example, if it were confirmed that extensor spasms were frequently triggered by vestibular disturbance, then greater efforts would be made to stabilise the head. It is already known that low frequency vibration or vestibular disturbance reduces spasms - parents and staff gently shake the children into a flexed position to relax them when placing them into a seat. If it were shown that certain aspects of proprioception modified the spasm response, then a seat could be designed to accentuate or mask the proprioceptive effect by, for example, adding a vibrator or using compliant surfaces that reduce the perception of pressure or contact.

This work has shown that extensor spasms are measurable and can be described during every-day classroom activities with relatively simple technology. It has also shown that seat configuration influences spasms. The instrumented seat designed under this research offers an opportunity for larger scale research into the nature and influences of extensor spasms in collaboration with neurologists to bring a clear direction to this engineering research.

Spasms patterns and characteristics vary considerably from child to child and with time. They are triggered and modified by a wide variety of environmental and and tactile stimuli, and are especially sensitive to changes in the emotional state of the child. They are profoundly affected by posture, and in particular by hip flexion angle and hip abduction angle.

Finally, movement and compliance in the supporting surfaces reduces spasm intensity. This has been known intuitively by the parents of children with extensor spasms for a long time; however, within the limitations of the small sample of children, this work suggests that support compliance has a positive effect on the child making seating more comfortable, more functional, and offering an opportunity for motor development.

17.2.4 Iterative design methods for dynamic seating

The design of dynamic seating presented challenges to the usual iterative design process developed and used at BIME[45]. Because of the complexity of the dynamic seat, the time required to design prototypes that could be used to assess feasibility was long. A method for early feasibility assessment without complex design and manufacture was needed, and to this end the soft and semi-soft prototype evaluation methods were developed (Chapter 4). These enabled complex seating concepts to be trialled with very little investment in time or other resources. Findings from evaluations conducted with these methods proved to be sufficiently representative of the outcomes with the fully functional prototype designs to be useful. Several examples are given below:

1. The approach to seating trialled in soft prototype was confirmed as feasible in the semi-soft and fully functional prototypes. Minimising backrest movement and increasing leg movement was a useful approach.

2. The need to hinge the seat backrest was suggested by the semi-soft prototype, and confirmed by the evaluations of the independent and second independent seats.

3. The gains in pelvic and spinal symmetry from allowing independent leg movement that were suggested by the semi-soft evaluation were realised in the fully independent seat.

To be most effective, evaluations conducted with this method need to be planned and carefully observed, particularly with a demanding population such as the severely disabled children that participated in this research. They can require large numbers of people to provide sufficient support as well as capture the outcomes and maintain the child's interests. They also require the team to work together well, and communications to be good. The semi-soft evaluations were good examples of well planned evaluations that provided much useful information. Nevertheless, quick spontaneous evaluations are not without value, and can still provide useful information to the design team. For example, the first soft prototype evaluation conducted in R1's home was spontaneous(Section 8.1.2), yet it provided the foundations for the rest of the research presented here. The conclusions drawn from that evaluation regarding positioning, stabilisation and spasm resistance were later shown to be valid for A1 and R1 when in fully functional seats.

This thesis presents the conception of soft prototyping, and its use in research into passive dynamic seating systems where the net energy transfer from the user to the seat is equal to or greater than the energy transfer from the seat to the user. The Whole Body Dynamic Seat is complex and its design has required research into many aspects of how a child with whole body extensor spasms reacts and responds to seating. However, the seat is still unable to modify its response to the child's movements with reference to the context or history of the child's movements. The support that a parent offers to a disabled child does function in this way, and to implement such support requires the design of an active seat. The soft prototyping method could equally be applied to the evaluation of intelligent active seating or other physical support systems employing intelligent control systems aware of the users immediate movement context and history. The method could be used to conduct a pilot study into the configuration and design of such an active physical user interface, requiring no investment in its hardware and software design, but yielding useful information on its specification and user interface design.

In summary then, **the newly developed method of evaluating soft and semi-soft prototypes, while not being a substitute for the evaluation of fully functional prototypes, can rapidly provide useful**

information about the feasibility of a design concept without requiring a large commitment in time or materials. These methods are especially relevant to the design of complex mechanical support systems such as dynamic seating and should be considered during the feasibility and concept development stages of design.

17.3 A final thought

Neither adults nor children intuitively adopt single fixed positions for optimum function. We constantly adapt our posture to the subtleties of the task in hand. Why then do we fix disabled children in static positions, inhibiting their ability to move, communicate, interact and develop socially? The default position should be that children are provided with every possible opportunity to explore movement and learn postural and functional control for themselves. The dynamic seating presented in this thesis that enables functional movement and allows a child to experiment with movement in a supportive environment, is a small step towards realising the aim of an intelligent, actively adaptive and supportive environment that recognises the disabled child's level of control, and continuously provides just as much help as is needed; thus allowing the child to problem-solve his own disability and start to wrest control of his body back from the chaos caused by damage to his brain.

Chapter 18

Further Work

18.1 Dissemination strategy

This work is of value to the rehabilitation engineering and therapy communities in both practice and research. The outputs from the knowledge gained during this research are:

18.1.1 Conferences and Publications

At the time of writing, the technology described in this thesis has not been protected with a patent. In order not to defeat a future patent application which is currently in progress, and to support a nascent commercial collaboration, this work has not been published. However, once the patent is in place, several papers covering aspects of this research will be written. They are:

Seat Design: A paper will be written describing the seat design and its foundation on observation and measurement of children with whole body extensor spasms. It is anticipated submitting this paper to 'Disability and Rehabilitation: Assistive Technology'.

Design method: This paper will describe the soft and semi-soft prototyping method in more detail than the RESNA conference abstract[67]. It is anticipated that this paper will be submitted to 'Medical Engineering and Physics'.

Foot support: A short case study paper will be written describing the foot support work, including the soft prototype evaluated by an adult in Cambridge. It is anticipated that this short paper will be submitted to 'Disability and Rehabilitation: Assistive Technology'.

Spasm characteristics: A paper describing spasm characteristics from analysis of the sensor and video data. Further analysis will be carried out to broaden the scope and detail of this paper beyond that submitted in this thesis. This paper will be submitted to 'Clinical Biomechanics'.

18.1.2 Technology transfer

It is a primary aim of this ongoing programme of work that it should result in commercially available seating that is able to be used by children with whole body extensor spasms and also by those with lesser disability so that they can also benefit from opportunities for movement and the ability to functionally adapt their posture.

18.2 Further research

18.2.1 Investigating Intuitive Dynamic Support Strategies

Disabled and able children have been provided with dynamic support for millennia by their parents as they learn to sit, stand, and walk. A five month old baby sitting on his mother's lap may not be able to sit unaided, but he sits with support from his mother's hands about his trunk or maybe his hips. His mother provides the support he needs, and importantly for his functioning, adapts her support to his movements. If he reaches for a toy she will adapt her support to his desired movement, allowing him to change his truncal posture and reach out with his arm while still providing sufficient support to prevent him from over-balancing and falling. She does not leave him in his modified position, but when he has reached the toy and he attempts to sit symmetrically again she supports his own restoration of stability and assists his return to an upright sitting position.

This strategy of providing adaptive support to a child learning to sit is intuitive. Parents are not trained in how to support a child yet they are able to provide continuous adaptive support that allows the child to progressively learn how to sit independently. Likewise, during this work, it has been observed that the parents of disabled children are able to provide effective dynamic support to children with whole body extensor spasms. The support strategies of these parents were observed, and the seat design that is the subject of this thesis has evolved from that strategy, however the detail of what forces the parent applies to the child during a spasm is opaque to an external observer, whether that observer is measuring the motion or ground reaction forces. The parent and child form a closed system, and the forces internal to that system cannot be determined without interposing some kind of sensor within the system.

An intern, supervised by the author, was recruited for a ten month project that began in October 2011 to design a multi-axis force and position sensor that will be held by parents and therapists and used to measure what forces they apply to a child when the child experiences a spasm. The sensor contains novel three-axis force sensors that measure the force applied between the child and parent. This force is the result of the child's action and the parent's response. The sensor also contains a solid state gyro that measures rotation of the sensor.

The combination of three-axis force measurement and rotational accelerometry will enable parents' responses to children's spasms to be measured. This information can then be used to assist with the design of a dynamic seat that may respond to its occupant in a similar way, mimicking the successful strategies that parents already use (Figure 18-1).

It is anticipated that a system capable of producing this kind of response will require a net energy input and thus will be an active device akin to an exoskeleton in its function if not its appearance.

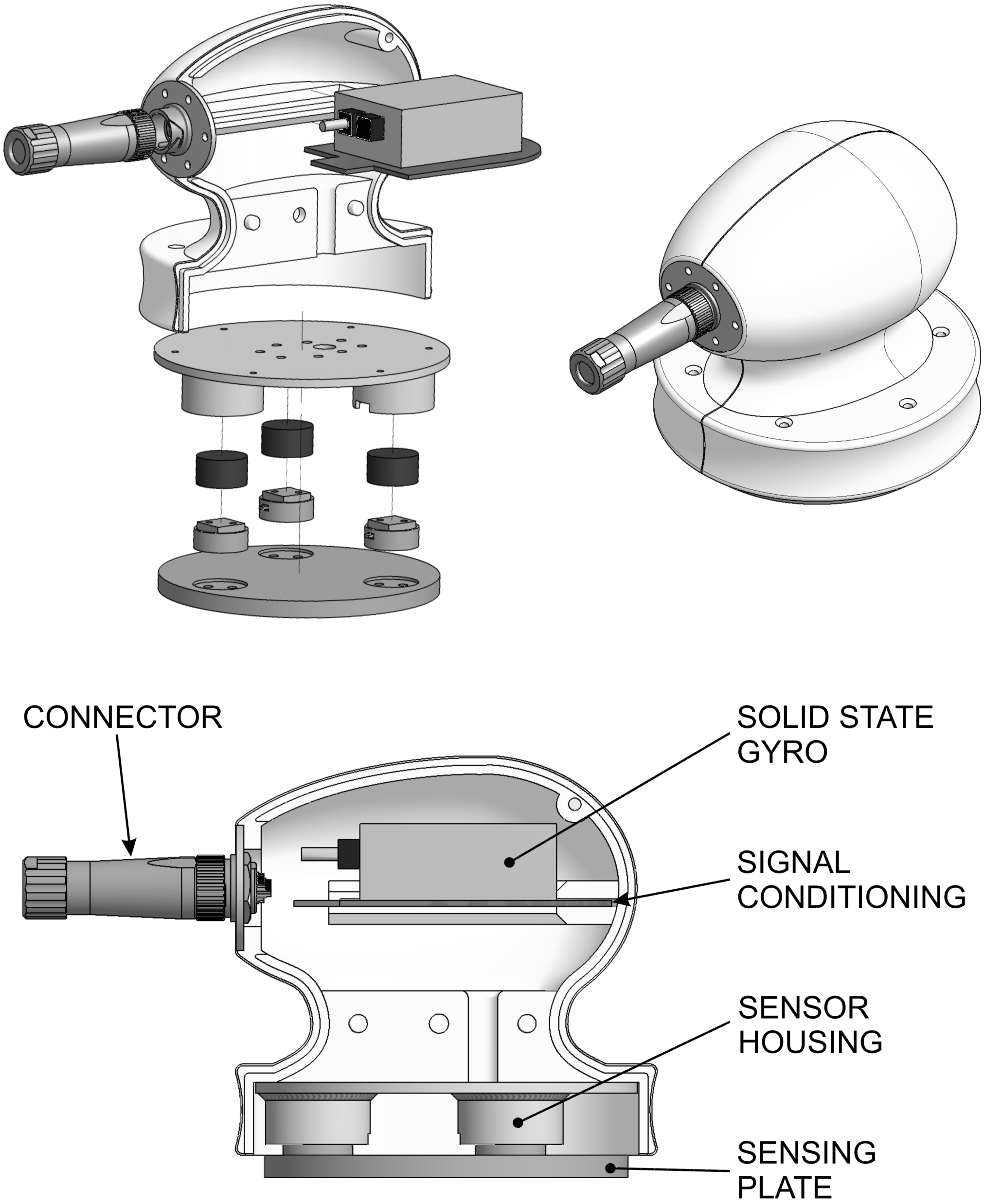

Figure 18-1: Drawings of the force sensor designed for measuring the forces that parents apply to children when they are supporting them during extensor spasms. The sensor incorporates a solid state gyro and three three-axis force sensors. It is able to measure force in three axes, torque in three axes, and angular acceleration in one axis.

The sensor will be used in a study of parents' and therapists' intuitive support strategies for children with whole body extensor spasms. Children will be supported by their parents using the sensor in one hand to measure the forces they apply as their child extends. The gyro in the sensor will enable the force and position of the parents' actions to be measured. Video recording of the sessions will capture the techniques used by the parents and therapists. This study will inform further development of the seat design, and possibly suggest alternative dynamic support strategies.
At the time of writing (August 2012) the study protocol has been approved by NHS ethics, and the team is waiting for research governance approval.
Following discussion with a paediatric occupational therapy department at the Royal United Hospital in Bath, it has been found that this sensor is also likely to be useful in a clinical context as an assessment tool for therapists. It would provide quantitative assessment of resistance, stiffness and forces that a child is capable of applying voluntarily or involuntarily, as well as measuring ranges of motion with higher precision and objectivity than is possible with current subjective assessment. The sensor is being designed to meet both these applications, and will be trialled in the occupational therapy department on completion of the dynamic support study.

18.2.2 Investigating the Impact of Dynamic Support on Social and Physical Functioning

A study has been designed and a grant applied for to investigate the impact of dynamic seating on children with cerebral palsy and extensor spasms falling into Chailey Sitting Ability Level 1 and Level 2. Using a rationalised version of the seat designed for the work described in this document, sixteen children will be supplied with a dynamic seat, and their functioning will be measured in physical and social domains. Measurements are likely to include:

1. The Vineland 2[68] outcome measure will be used to assess the child's ability to communicate using verbal and non-verbal methods, including non-verbal vocalizations and postural adjustments.

2. Interactions between staff and the child will also be measured in a classroom context to assess the quantity and quality of interactions with staff and other children. Examples of parameters to be measured include eye-contact duration and frequency, directed vocalization towards and by the child, and staff attention directed towards the child.

3. Physical function will be measured, an example of which is the ability of a child to operate a switch placed in a range of positions on a tray mounted in front of the child[13].

The first phase of the project incorporates three tasks: recruitment of children for the main study; rationalisation of the current seat design for simplicity, manufacturability and affordability; and then manufacture of eight seats to the new design.
The second phase will be the main study which will take place over one year. It will be an A/B/A study. The final six months of the project will be used for analysis of the results and dissemination activities See Appendix A for the submitted research proposal.

18.2.3 Does dynamic support enable infants with cerebral palsy to learn adaptive strategies for control?

This proposal for a project is a logical step forward from the existing dynamic seating research, which has suggested that children with cerebral palsy are able to learn strategies for functional control of their bodies when placed in a support that enables them to experiment with movement. The proposal is based upon conclusions drawn from Section 2.3 of the literature review, and on observation of apparent learning of functional movement strategies by a child evaluating the whole body dynamic seat (Chapters 15 and 17).

Children develop fastest and adapt to disability fastest when they are very young: less than a year old. The rate of development, learning and adaptation decreases with age, so it is advantageous to support the development of functional movement strategies from as early an age as possible. This proposed project is the design of dynamic support surfaces for children aged six to twenty four months who have been identified as being at high risk of neuromotor disability such as cerebral palsy. The project will design a dynamic support system, and evaluate its use with children in this age-group, measuring developmental and functional outcomes.

A local consortium of experts has been formed in developmental neurology, neonatal care, rehabilitation engineering and occupational therapy. This team is supported by a nationally leading neurologist and occupational therapist.

18.2.4 The design of dynamic head and foot supports

Not all children with extensor spasms require a fully dynamic seat. Many children and adults would benefit from a dynamic head support or foot support mounted on their existing seating. This would be a cost effective and much simpler solution for many. Some work has been done to lay the foundations for the design of these products, but further work is required to turn these concepts into products.

Variously sized versions of the independent dynamic foot support would be suitable for adults and children with extensor spasms. The independent foot support has only been evaluated as a soft prototype, though it has been implemented successfully in the children's whole body dynamic seat. The method and outcomes of the soft prototype evaluation are described in Section 13. Further work is required to design the support to fit a wide range of existing children's and adult wheelchairs, and to evaluate the concept with users. Designing for universal mounting is a common but challenging problem in rehabilitation technology where there is little standardisation of mounts for accessory products between manufacturers.

A modest amount of funding such as that obtainable from the product focussed National Institute of Health Research i4i [`http://www.nihr.ac.uk/i4i`] scheme would be suitable for this project. It is likely that design and evaluation could be completed within a year.

An independent dynamic head support would benefit children and adults with extensor spasms in their upper body. A concept for this device has already been designed under an undergraduate project supervised by the author. A key outcome of this project was the measurement of head movement paths in six axes. This measurement enabled the required motion for an anatomical head support to be

calculated. Such a head support is likely to enhance the functional head positioning of a person with difficulty controlling head movement due to either muscle weakness or spasm.
A project to design a dynamic head support suitable for most wheelchairs would be likely to be funded from similar sources to the dynamic foot support described above.

18.2.5 Active adaptive support technology

This research has demonstrated the potential of whole body dynamic seating to support children who would otherwise be unable to sit successfully. Observation of the ways in which parents intuitively dynamically support children has suggested that an active dynamic seat would be more effective that a passive dynamic seat.
An active seat would also enable a much wider degree of controlled postures as well as a wider range of enabled movements compared to a passive dynamic seat. Key objectives for this research would be:

1. *A modular active seat* using distributed control systems to sense forces applied by the user and respond to the user's inputs with intelligently controlled resistance or assistance, enabling functional movements. The seat would allow controlled extension, flexion and lateral deviation.

2. *A rules based control system* capable of interpreting a series of rules into constraints applied to the motion of the seat. Examples of rules might be:

   (a) "Hip extension must not exceed 70°"

   (b) "Lateral spinal deviation must not exceed more than 5° for more than twenty seconds."

   (c) "Left hip torque must not exceed 10Nm"

   Such a control system would continuously evaluate the position of the occupant and changes in posture by the occupant in the context of the system of rules that govern the movement and maintain the user's posture appropriately. So, for example, under Item 2b above, a lateral movement by the occupant to reach something on a table would be supported but not impeded, so long as it did not take more than twenty seconds to perform. After twenty seconds, the system would gently return the occupant to an upright position.

   Using a system of rules such as this would allow a user a significant degree of freedom of functional movement, while still ensuring that good posture is maintained and tendencies towards structural deformity are resisted.

   More dynamic rules could be implemented to maintain minimum passive exercise levels, or to actively train the occupant in functional or other beneficial or rehabilitative movements.

3. *A user programming interface* that would enable a therapist with a modest amount of training to design and program the rule set for an individual patient.

   It is important that a system such as this, that is is designed for use in a home or school for example, does not require technically qualified people to operate it. Its operation and configuration should not be placed beyond the abilities of a typical occupational therapist, for example. This aspect of the controller, though not directly related to the control of the system, is essential for the success and useability of the system as a whole. It is not a trivial piece of work, and is likely to be a research project in its own right.

This project is expected to require five years work and would be carried out in two phases. The first would be the design of a proof-of-concept of the sensor/controller/actuator system and implement it in a single degree-of- freedom active dynamic backrest. The second phase would be to extend this control system to a complete dynamic support system suitable for young children. The controller user-interface design would be carried out in parallel with phase two.
Though this technology would be developed initially for children with neurological disability, it would also be relevant to adults with disability resulting from, for example, stroke or traumatic brain injury. A consortium for this work is sought comprising BIME, the University of Bath, the Institute of Child Health and some local clinical centres (Bath, Salisbury, Oxford, etc).

18.2.6 Digital Manufacture of Personalised Assistive Technology

This is a proposal for a project to research a digital manufacturing path that could be applied in clinical contexts such as specialist seating, prosthetics and orthotics; as well as non-medical contexts such as seating for motor racing or high performance aircraft. Casting and moulding technologies are currently used in the provision of assistive technology such as specialist seating, prosthetic limb sockets, specialist shoe insoles, splints and spinal jackets. The application of advanced manufacturing technology to this context could significantly reduce the cost and waiting times for personalised products by reducing the time currently taken in assessment and manufacture using time and space intensive methods such as plaster casting and moulding.
It is proposed to take specialist seating as a context in which to develop this technology. Wheelchair seating has a major impact on the quality of life of its users, yet there has been little innovation in the area for decades. The service provided by the NHS is the best it can be with scarce available resources, but waiting times for assessment and delivery times for products are long.
A digital path from measurement to manufacture is envisaged encompassing the following stages: 1. Measurement - use of a compliant instrumented surface to determine the shape of the individual user of the resulting product. 2. Adjustment - adjustment of the measured shape by the clinician so that the delivered product achieves its therapeutic objectives. 3. Manufacture - construction of the delivered product from the digital shape using advanced manufacturing techniques including direct additive manufacture and automated assembly and modification of multiple simple sub components. 4. Delivery - Provision of the product to its user through a rapid and efficient service.

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Part VI

Appendix

Appendix A

A Proposal for Further Research

Following is a full proposal for three years of further research written by the author and submitted to Action Medical Research as an outline in November 2011. The outline was approved, and this full proposal was submitted in March 2012. The full proposal was declined by Action Medical Research, however alternative routes to research funding are being actively investigated at the time of writing.
The protocol following describes a 180k, three year programme to evaluate a smaller version (age 3-7) of the independent seat with sixteen children using an n=1 case study method. The aim of this research was to explore the functional gains that are may be achieved with the seat, and the range of disability for which the seat may be suitable.
The project was a collaboration with a consultant neurologist from the Community Child Heath department of Sirona, who provide community healthcare services to Bath and North East Somerset; and also with a UK seating manufacturer who agreed to collaborate on the design of the seat.
A further 10k/year charitable funding was obtained for the project from another charity for three years, in addition to two small charitable grants of 5k each.

Protocol: The Functional Impact of Whole Body Dynamic Seating on Children with Dystonic Cerebral Palsy

Tim Adlam, Bath Institute of Medical Engineering;

Dr Kate Martin, Dept. Child Health, Sirona Care and Health

1) BACKGROUND

Many children with cerebral palsy spend hours every day in a fixed “optimum” position, compared with comparatively short amounts out of the chair for therapy, school activities and daily living activities. If the children were not disabled, they would frequently adjust their posture to suit their activity. Rigid seating and their movement disorder prevents this from occurring, removing an opportunity for them to learn to control their bodies to communicate and interact socially[1,2].

In its previous research BIME and Great Ormond Street Hospital examined the seating needs of children with severe whole body extensor spasms from first principles. The team asked how an unplaceable child with a powerful whole body extensor pattern could be seated comfortably and functionally. This was achieved with a seat that helps stabilise the child’s head and trunk, while yielding to extensor spasms primarily in movement of the legs, and also in backrest movement [Figs. 3a, 3b]. This enabled the child to choose and maintain preferred postures. The research also showed that if the child’s spasms were limited by an end stop in the seat mechanism, the spasm forces rapidly and significantly increased.

This project will investigate whether whole body dynamic seating enhances functioning and engagement in an educational environment. This work will evaluate the impact of using such as seat on a group of sixteen children with a broader range of movement difficulties. It will measure impact on sitting ability, comfort and engagement in learning, daily life and social activities.

Action Medical Research aims to “*support children facing a life-time of challenges caused by disabilities such as cerebral palsy…*”. This type of seating could enable children with dystonic cerebral palsy to be more functional and more engaged with the people and activities around them.

2) HYPOTHESIS AND REASONING

That sitting in whole body dynamic seating by children with dystonic cerebral palsy leads to an improvement in functioning and engagement at school.

Recent work at BIME (Action Medical Grant AP1115)[3,4,5] has suggested that severely disabled children using whole body dynamic seating can gain function and experience increased social engagement. Examples of observed outcomes are:

i) The child was able to operate a switch independently in the dynamic seat, and was not able to operate it in his usual static seat. When sitting in the static seat, he appeared to be ‘locked’ by his spasms, and could not move his hand to the switch. Conversely, when in the dynamic seat, his hand movement was freer and he was able to use seat movement functionally to reach and operate the switch independently.

ii) The child's teacher observed that his vocalization and engagement with staff improved, possibly by drawing attention to himself and expressing his feelings with movement.

The proposed research will investigate the potential of whole body dynamic seating to facilitate functional movement and social and educational engagement. The previous study suggested that this novel approach to seating design has a potential to significantly improve outcomes for children with severe movement disorders; however this study was too small to confirm the generality of the approach. Thus there is a need for a larger study to evaluate the effectiveness of whole body dynamic seating for a broader range of children, enabling the benefit or otherwise of this approach to seating to be established.

3) METHODS

The hypothesis will be tested through evaluation of the functional impact of a whole body dynamic seat on sixteen children with dystonic cerebral palsy, recruited to the project from three clinical centres. This is the largest number of children that can be practically accommodated within a project of this scale. It is likely that there will be some withdrawals from the study due to external factors such as poor general health and non-study interventions. See Figure 1.

The research project and staff will be managed by Tim Adlam using a 'whole team' model proven in another multidisciplinary multicentre project where he is a local principal investigator [ESRC RES-354-25-0003, £752,016.22 at 80% FEC]. Experience in this complex project has shown that effective weekly communication across the whole team helps to build the team across disciplines and to enable the rapid identification and resolution of arising problems.

a) Inclusion Criteria

Children recruited to the project will have dystonic cerebral palsy across a range of severity from children with whole body extensor spasms who are unplaceable (Chailey Sitting Ability Level 1[6]) to children who are able to sit with conventional paediatric seating systems (Chailey Sitting Ability Level 2[6]). Both of these groups of children fall within the Gross Motor Function Classification System Level 5[7]. The ages of the children recruited will be between three and six years.

Recruitment to the previous project was challenging due to the general poor health and the number of non-project interventions experienced by the children. Thus the range of disability has been extended to enable a larger participant group to be recruited. This will also allow investigation into the suitability of the seating for children with a wider range on movement difficulties arising from cerebral palsy.

b) Phase 1 – Preparation and Design (18 months):

To support the evidence base for the configuration of the new seat design we will:

a) Study dynamic support strategies used by parents to support young children who are learning to sit; utilizing video recording and a new force sensor under development at BIME to classify and quantify parents' strategies;

b) Recruit children to the main evaluation study (see 'Inclusion Criteria' above);

c) Design a rationalized whole body dynamic seat; simplifying the design from the previous work while retaining necessary functionality.

c) Phase 2 – Evaluation (12 months):

The second phase will be a twelve month study of sixteen children sharing eight whole body dynamic seats. The study will use an A-B-A model: 2 weeks baseline (usual seating); 3 months measurement (dynamic seating); 1 month withdrawal (usual seating). This model will enable developmental changes that occur in the child to be assessed independently of the seating intervention. See Figure 2.

The impact of the seat will be assessed using functional outcome measures including:

- Sitting ability – this will be measured on the Chailey Sitting Ability Scale[6];
- Motor function, including core stability, will be measured and assessed using the Gross Motor Function Classification Scale[7];
- The Paediatric Pain Profile[8] will be used to measure comfort in seating;
- Educational engagement will be measured using video recording and relevant components of the Vineland 2 outcome measure[9]; Social engagement will be measured using video recording and assessed using measures based upon eye-gaze time and communication[10];
- Qualitative outcomes around postural adaptation and functional self-positioning will be observed, recorded and classified using video recorded from the classroom.
- Instrumentation will be built into the seats to provide a high resolution long term measure of activity, using systems already proven in the previous work.
- Other qualitative outcomes will be recorded through interview and written self-report from carers, teachers and parents.

d) Phase 3 – Analysis and Dissemination (6 months):

The final phase of the project will analyse the video and the sensor data and publish the findings. It is also expected that if the project is successful, then the seat will be brought to market.

e) Ethics, Consent and Data Management

Two applications are required for ethical approval to the NHS Research Ethics Service (IRAS). The first is for the intuitive support methods study at the beginning of the project, and is an extension of an existing application currently under review.

The second is for the main seating study. The RUH NHS Trust research support unit advised that this ethics application should be submitted during the first year of the project.

Initial approaches to families will be made by clinical staff with whom they are already familiar. The project will be presented by a member of the research team. The family will be able to give consent or ignore the approach. If they do join the project, they will be able to leave at any time without giving reasons. Explicit consent will be gained for photography and video recording, including the scope of usage for such media.

Digital project data will be stored on password protected computers and backed up on secure University networked storage and multiple hard disks. Paper project data will be stored in locked filing cabinets in a secure office.

f) Project Support

The project will be supported and reviewed every six months by an advisory panel comprising:

Dr Lucinda Carr – Consultant Paediatric Neurologist, Great Ormond Street Hospital.

Prof. Roger Orpwood – Retired (2010) Director of BIME.

Alison Wisbeach – Retired (2010) Head of Occupational Therapy, Great Ormond Street Hospital.

Noel McQuaid – Technical Director, James Leckey Design (major UK seating manufacturer).

The panel will meet with the research team and investigators to review all aspects of the project.

A product designer from James Leckey Design will provide a quarterly review for the project engineer on aesthetic design and design for manufacture.

Two children and a clinical therapist will advise the engineer on the design of the seat.

4) OTHER RESEARCH

a) By Applicants

Compliant Seat Design (AMR Project AP1115)

This previous project formed the foundation of this research, designed, built and manufactured an innovative test seat to evaluate whole body dynamic seating.

Design of an Anatomical Dynamic Head Support – 2010/11

This project was conducted as a six month undergraduate research project by a student from the University of Bath Department of Mechanical Engineering. After an initial literature review did not find any data on head movement paths. The student used video recording and a 3D motion capture system to measure normal head movement paths; and designed a dynamic head support that mimicked natural movement paths.

EQUIP Project – 2011/12

In collaboration with the Royal United Hospital Department of Children's Occupational Therapy, an intern at BIME is designing and building the sensor that will be used to measure the forces applied by parents to children with extensor spasms. He will be evaluating the sensor with a small group of children in 2012. This is a pilot of the parental support study described in this protocol.

b) By others in the field

Most published dynamic seating studies are evaluations of existing commercial seats[11,12]. Brown et al[13] measured the forces and torques applied by children with extensor spasms to static seating.

Other relevant work is in the field of positioning and child development, such as McEwens work[1,2], showing that posture affects communication and engagement; and deGraaf-Peters work[14] suggesting that allowing disabled children to experiment with movement can improve their postural control.

5) DIFFICULTIES ANTICIPATED

a) Recruitment and retention of participants

Following difficulty with recruitment and retention during the previous work (AMR grant AP1115), an alternative strategy has been employed where three clinical centres (Bath, Oxford and Aylesbury) will identify children for the project from their own patients. The disability threshold for inclusion in the project has also been lowered, increasing the size of the population that is eligible to participate.

Some participant withdrawals from the project resulting from external factors such as changes in condition and unrelated medical interventions are expected to occur due to the complexity of disability in the study population. However, the study will remain valid without a full complement of participants because of its A-B-A baselined design.

6) FURTHER WORK EXPECTED

a) Commercialisation of the seat design

It is intended that if the outcome of this research shows that there is significant benefit to the identified population in using whole body dynamic seating, then the seat designed under this research programme will be brought to market as a product in cooperation with a major seating manufacturer, after a period of product development following this research. Additional related products (accessory head and foot supports) may also be brought to market.

b) Design of positioning/seating systems for ex-NICU babies

With the aim of extending this work to the age when a child is most able to adapt to brain trauma, BIME is developing a collaboration with the neonatal intensive care unit (NICU) in Bath and the community paediatrics team. This work will investigate the design of support equipment for ex-NICU infants with the aim of supporting their development and functioning during the ‘golden window’ of their first two years of neurodevelopment.

c) Research into active seating

It is planned that a future research project based on this work will research active dynamic seating that is able to provide active adaptive dynamic support more closely tailored to the users’ needs than can be achieved with passive spring based dynamic systems. This will be in collaboration with the robotics and control group at the University of Bath Department of Mechanical Engineering.

7) FINANCIAL JUSTIFICATION

a) Posts and Salaries – Pay Calculated with Sirius Web [http://www.siriusweb.leeds.ac.uk]

Occupational Therapist, 60% FTE, NHS Band 7, Spine Point 30, Months 6-36: The occupational therapist will be the senior researcher and will be involved in all aspects of the project except the first phases of project set-up and design work. In phase 1 the therapist will run the initial support method study investigating how parents intuitively support their children. In parallel with this work the therapist will recruit children for the main study from the three clinical centres, and others if needed. In phase 2, the therapist will run the evaluation study, including introduction, assessment, preschool and school staff training and periodic data collection. The therapist will analyse the study data during phase 3.

Design Engineer, 80% FTE, NHS Band 6, Spine Point 28, Months 1-36: The design engineer will design the new rationalised seat with support from the industrial product designer. The engineer will recruit the therapist and children who will assist with the design work. The engineer will also build the seats; assist the occupational therapist with the evaluation work during the main trial; visit the research sites to provide technical support; and assist with the data analysis, especially the sensor data.

b) Consumables

Seats and Instrumentation: The new seats will be designed by the project research engineer and built at BIME. The seats will be instrumented with force sensors to enable long term quantitative assessment of spasmodic and volitional movements. Force sensing will be used (rather than movement sensing), because the previous project showed that it reveals low force and transient muscle contractions that are difficult to measure as movement, because of friction and inertia in the seat mechanism.

Travel: The initial intuitive support project and the main seating study will require the researchers to visit the schools of the participants to introduce the project, collect data and provide technical support.

The expert advisory group is a key part of this project, and will be monitoring progress as well as advising on the methods and direction of the work taken. The group will meet with the investigators and researchers every six months. The costs allocated include room hire and travel costs. Because of the geographical dispersion of the advisory group between Northern Ireland, London and the South West of England, meetings will be held at a mutually convenient central location.

The Leckey Product Designer and the Engineer will meet four times per year to review product design aspects of the new seat.

APPENDICES

A. REFERENCES

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B. FIGURES AND TABLES

a) Project Gantt Chart

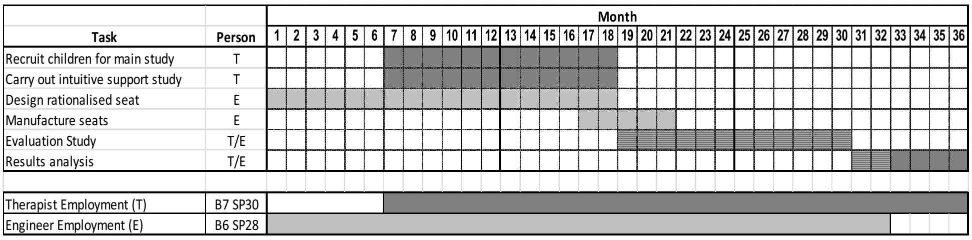


Figure 1: A Gantt chart of the whole project, showing the three project phases and the employment periods for each member of the research team.

b) Phase 2 Gantt Chart

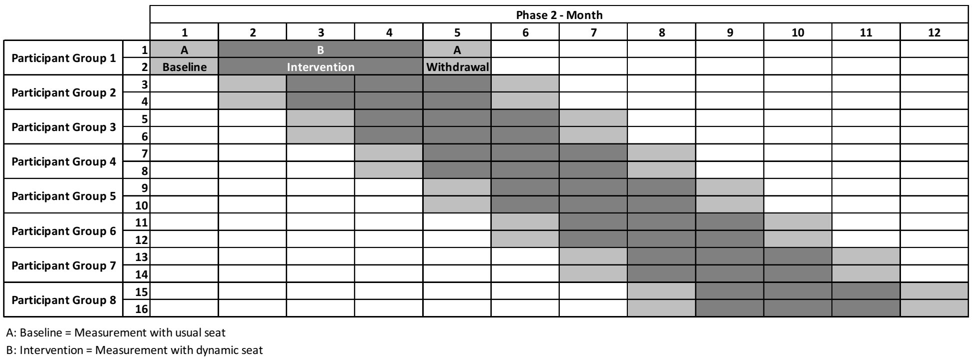


Figure 2: A Gantt chart of the evaluation schedule for Phase 2 of the project. Eight seats will be built so that in the event of damage, faults or unavoidable delays in seat handover, a working seat can be substituted quickly and disruption to the study schedule minimised.

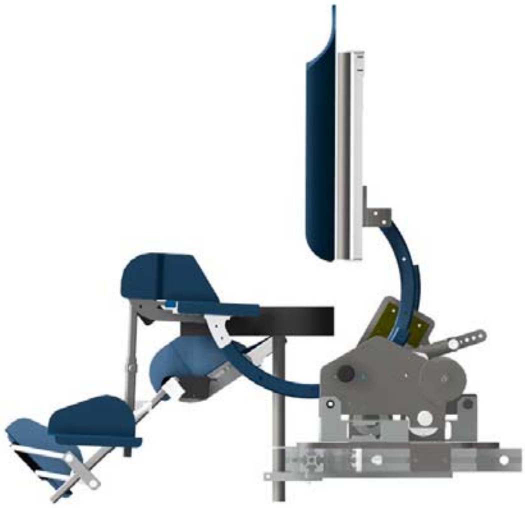


Figure 3a: A drawing of the previous whole body dynamic seat, showing the child's legs in flexed and partially extended positions.

Figure 3b: A photograph of the previous seat in use in the child's school.

Appendix B

Calibration and Error Estimation

The sensors were calibrated for measurement. The load cells and angle sensors were used with their factory tolerances and calibrations, which were considerably tighter than the other uncertainties in the measurements.

B.1 Angle calibration

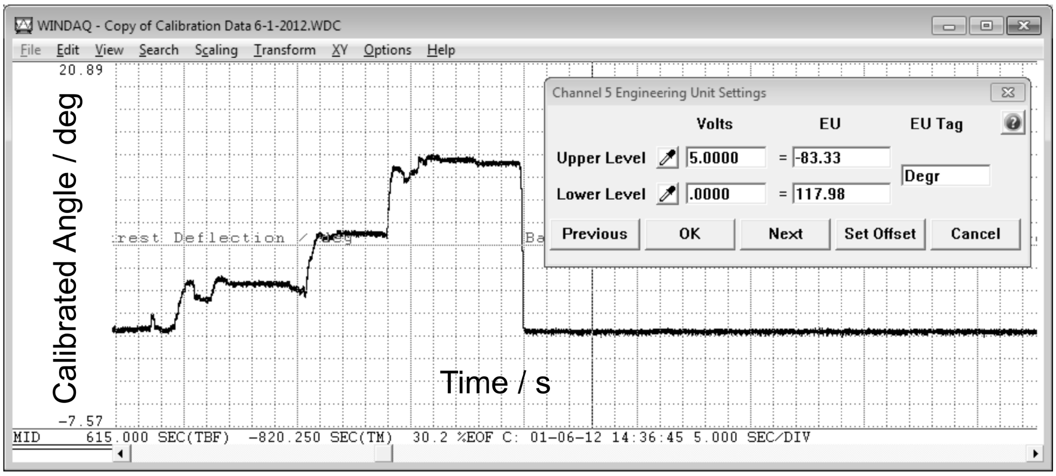
The angle sensors were calibrated using a goniometer clamped parallel to the seat which was sighted against the seat back and leg support assemblies. This technique gave measurements of angles consistent to $\pm 0.5°$, which were sufficient for the purposes to which the data was being applied. The angle sensor systems were calibrated linearly with the data logger software, assigning known angles to high and low voltages. An error analysis taking into account the sensor tolerances is given in Section B.4 below. The angle sensor systems were calibrated with the data logger software, assigning known angles to high and low voltages. Figure shows the angle calibration data for the left hip potentiometer and the backrest draw wire sensor. Graphs of the hip and backrest calibrations are shown in Figure B-1.

B.2 Leg Torque calibration

The load cells used to sense torques were built into leg and backrest mounting mechanisms, rather than into the moving components for the reasons stated in Section 14.3.3. This decision complicated the calibration of the sensors, as the leg and backrest supports and their corresponding load cells did not have a common centre of rotation. A diagram showing the dimensions to the leg support centre of rotation and the leg load cell centre of rotation is given in Figure B-2.
The load cell outputs were calibrated with the data logger. Factory calibration certificates supplied with the load cells confirmed that they were high accuracy sensors for this application. They were temperature compensated full bridge cells where, at their rated capacity of 75kg:

$$\textit{nominal calibration} \leq \textit{actual calibration} \leq \textit{nominal calibration + 1.5\%}$$

BACKREST ANGLE SENSOR CALIBRATION



LEFT HIP ANGLE SENSOR CALIBRATION

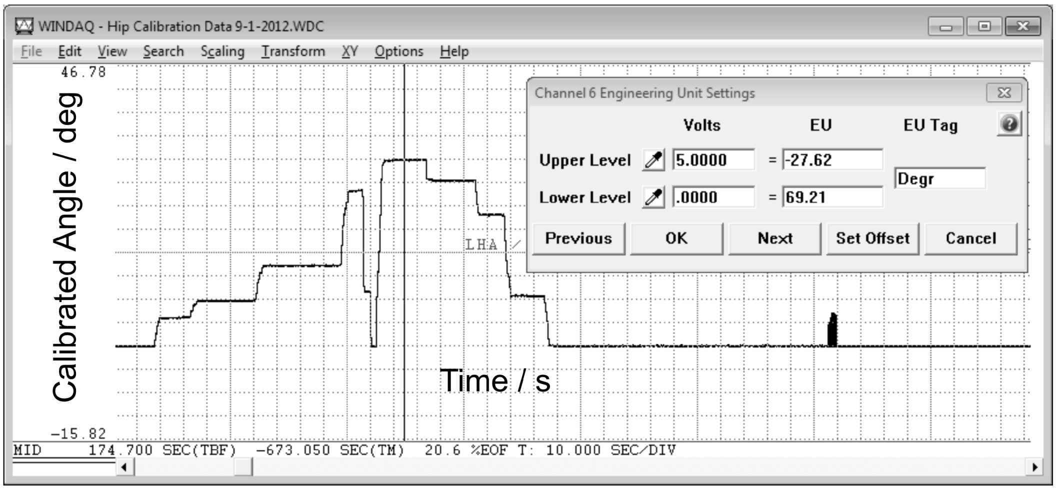


Figure B-1: Graphs of backrest and left hip angle sensor outputs using the data logger software and its calibration tool. This software allows a gradient and offset to be applied to sensor data.

Referring to Figure B-2, the equation relating the Load Cell force Q to the applied Torque T can be determined.
Given that:

Q	=	Measured load cell force;
x	=	Load cell moment arm;
P	=	Force applied by child;
R	=	Moment arm of P on leg support;
T	=	Torque applied to leg support
θ	=	Rotation angle of leg support;
r	=	Effective moment arm of P on load cell;
A	=	Horizontal offset of rotation centre;
B	=	Vertical offset of rotation centre;

Taking orthogonal moments about the leg load cell centre of rotation:

$$
\begin{aligned}
M_{y(loadcell)} &= PCos\theta.(A + RCos\theta) \\
M_{x(loadcell)} &= PSin\theta.(B - RSin\theta) \\
Qx &= M_y - M_x \\
Qx &= PCos\theta(A + RCos\theta) - PSin\theta(B - RSin\theta) \\
Qx &= Pr \\
Qx &= P[Cos\theta(A + RCos\theta) - Sin\theta(B - RSin\theta)] \\
Rearranging &: \\
P &= \frac{Qx}{Cos\theta(A + RCos\theta) - Sin\theta(B - RSin\theta)} \qquad \text{(B.1)} \\
But &: \\
T_{LegSupport} &= PR \\
Therefore &: \\
T_{LegSupport} &= \frac{RQx}{Cos\theta(A + RCos\theta) - Sin\theta(B - RSin\theta)} \qquad \text{(B.2)}
\end{aligned}
$$

For a plot of P against θ where $P = f(\theta, Q)$ and $Q = 1N$, see Figure B-3.
Plotting Equation B.1 with a zeroed load cell measurement and incorporating the factory calibration of the load cell, the following data was measured against known values generated with the force application tool shown in Figure B-9. Angles were measured with the sensors. This graph is shown in Figure B-4.

A best fit of this line was not used for calibration because of hysteresis in the system due to friction and stiction. See Figure B-5.
An alternative approach was taken to calibrate both the backrest and leg supports that was independent of friction and stiction, and did not rely on the linearity of the springs for consistent results.

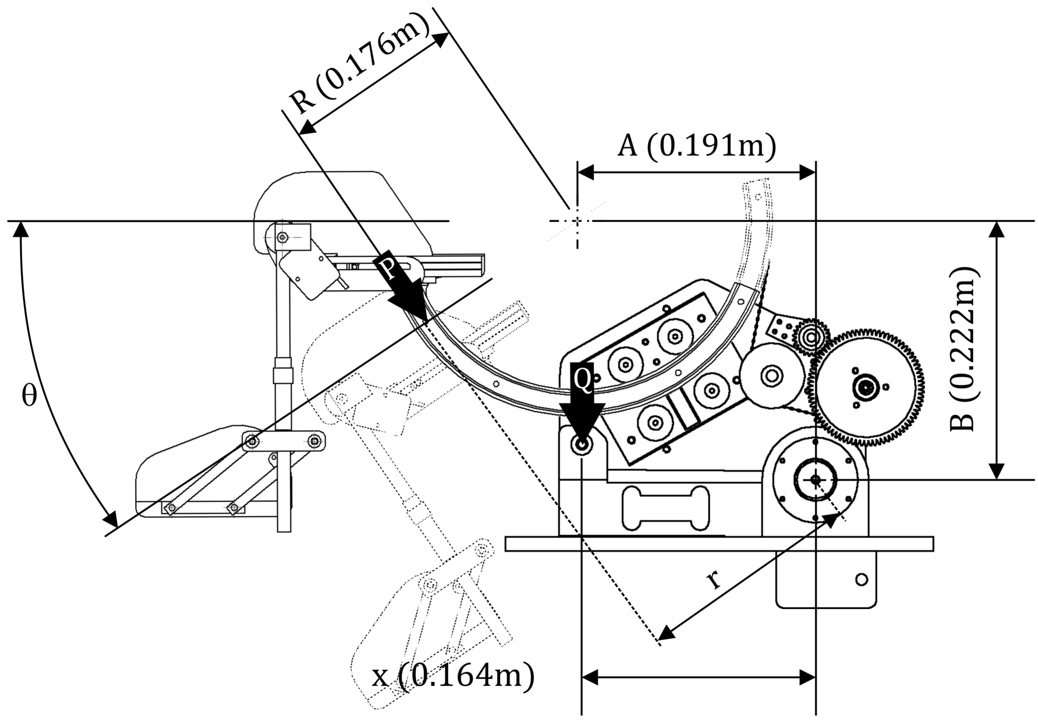


Figure B-2: A diagram of the dimensions relating the load cell force Q to the applied force P.

The leg supports (and backrest) were calibrated using a spread of static measurements across a range of angles and applied forces. These enabled a three dimensional surface to be fitted to the measured parameters for Angle(θ) and Load (Q) on the x and y axes, with the known applied force P on the z axis. See Figure B-6. Comparing the values of P derived from the equation with the real values of P for identical input values, the RMS error was 1.45N.
Where P = applied force, θ = leg support angle and Q = load cell output; the equation for the surface fitted to the calibration data was:

$$P_{leg,R=0.176m} = -29.59 - 0.1452\theta + 0.7159Q - 0.008325\theta^2 + 0.007117Q\theta + 0.0000346\theta^3 + 0.0001903\theta^2 Q \tag{B.3}$$

Table B.1: This table shows values for measured P and applied P for a series of angles as the leg support was extended under increasing load.

Actual P / N	**Load Cell Force Q / N**	**Measured P / N**	**Angle θ / deg**
0	0	1	0
19.62	62	28	0
29.43	90	40	0
39.24	106	48	0.91
49.05	119	55	2.7
78.48	141	89	24

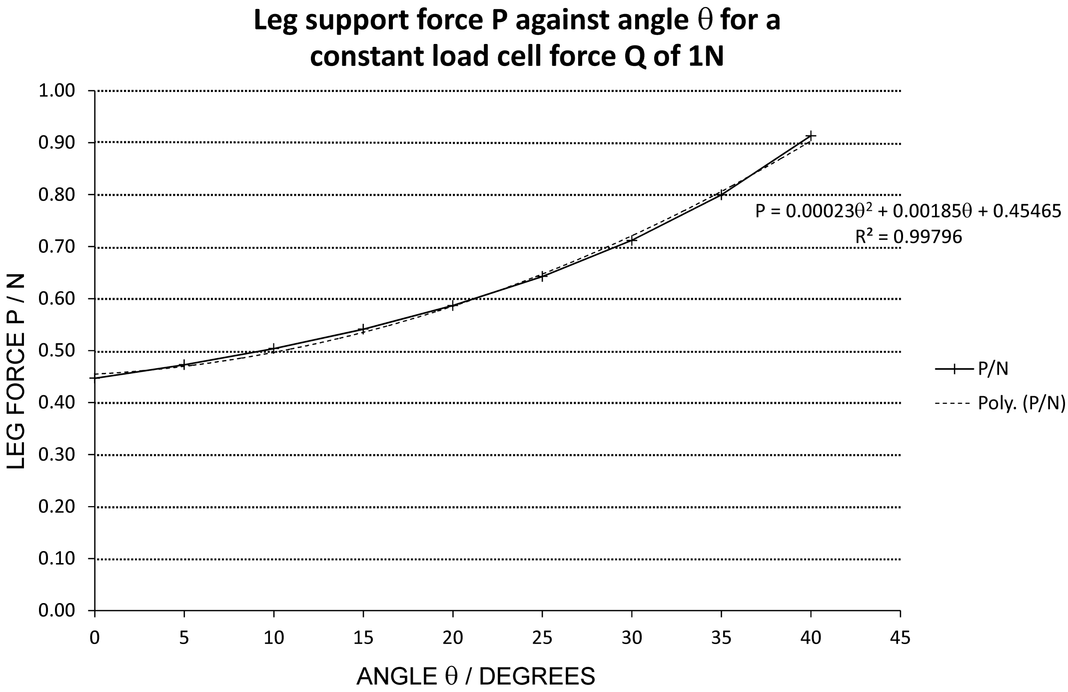


Figure B-3: An analytical plot of leg support force P against leg support angle θ, for a constant load cell force of 1N.

This method of calibration is independent of hysteresis in the nominally linear torque/angle relationship caused by friction in the system.

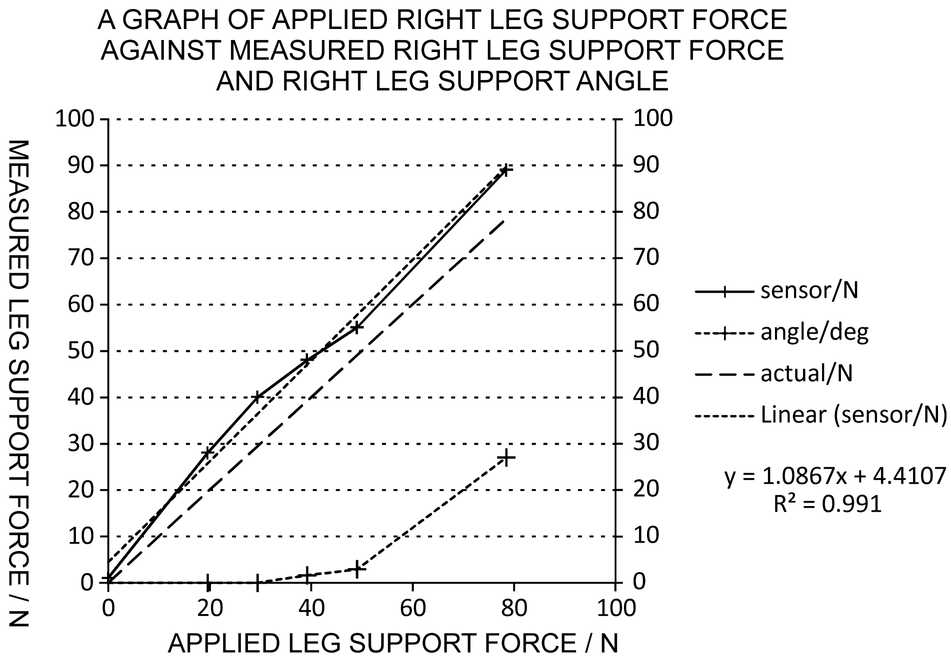
B.3 Backrest Torque calibration

The backrest torque analytical equation, using a similar method to that used for Equation B.2 is:

$$TorqueT_{backrest} = \frac{RQx}{Cos\theta(RCos\theta + A) + Sin\theta(RSin\theta - B)} \tag{B.4}$$

$$ForceP_{backrest} = \frac{Qx}{Cos\theta(RCos\theta + A) + Sin\theta(RSin\theta - B)} \tag{B.5}$$

A diagram showing the relevant dimensions is shown in Figure B-7.
A plot of Equation B.5 for $P_{backrest,Q=1}$ is shown in Figure B-8.
As with the leg supports, the backrest was calibrated using a three dimensional surface derived from a set of applied forces, set angles and measured forces across the range of seat movement and a range of forces.
Where P = Applied Force, θ = backrest angle, and Q = Load cell output force; the equation for the surface is:



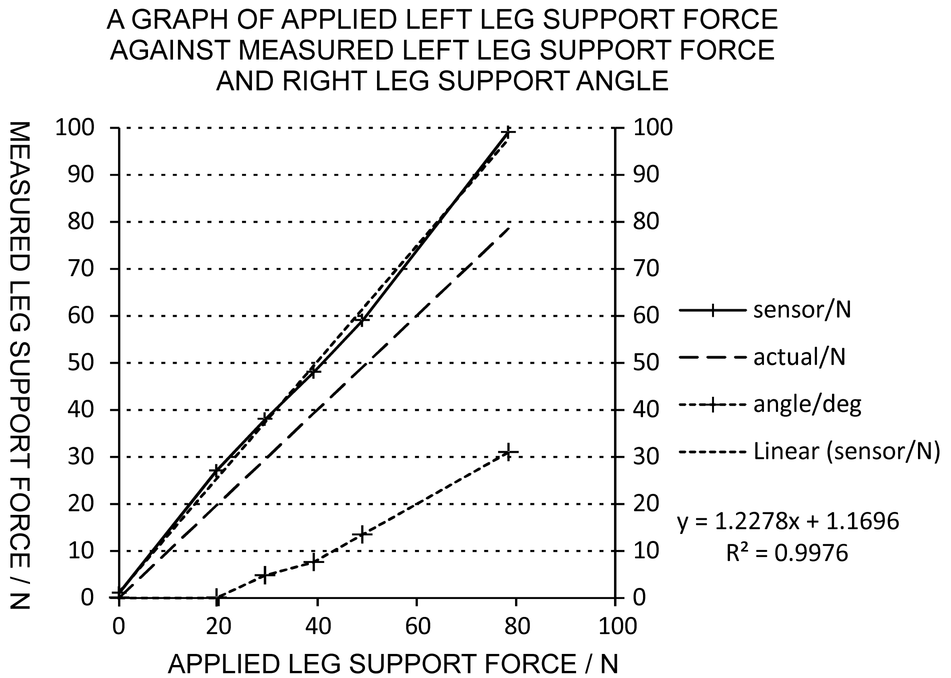


Figure B-4: Two graphs of measured force data against applied force data for the left (BTM) and right (TOP) leg support hip joints. The graph shows a multiplied error in both data sets, but with good linearity and near zero intercepts. The exact cause of this discrepancy is not known at this time however it did not prevent an accurate calibration.

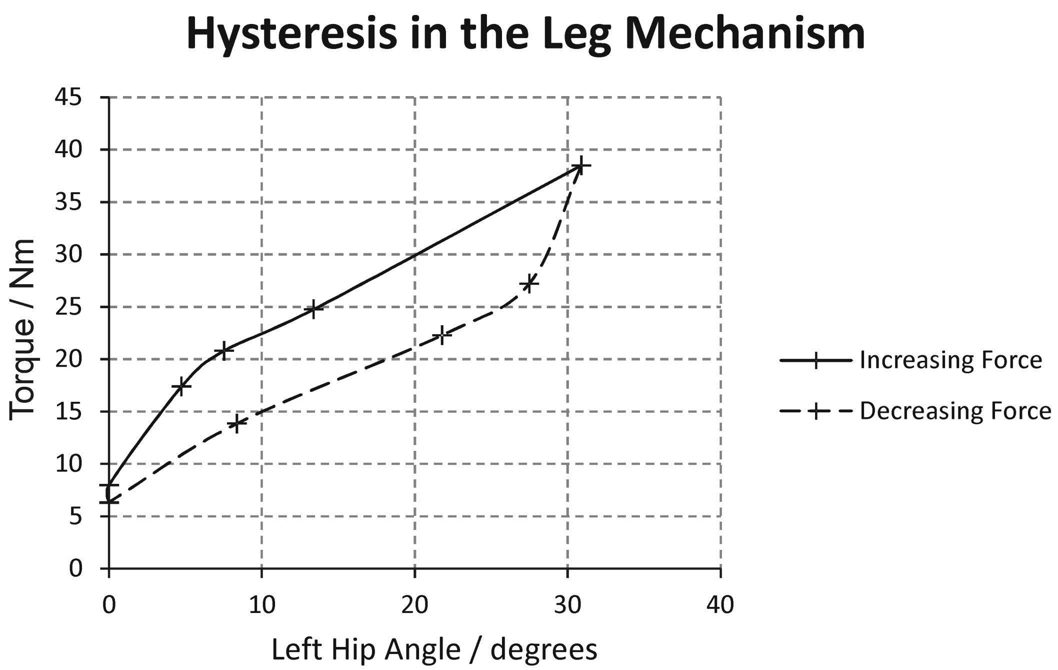
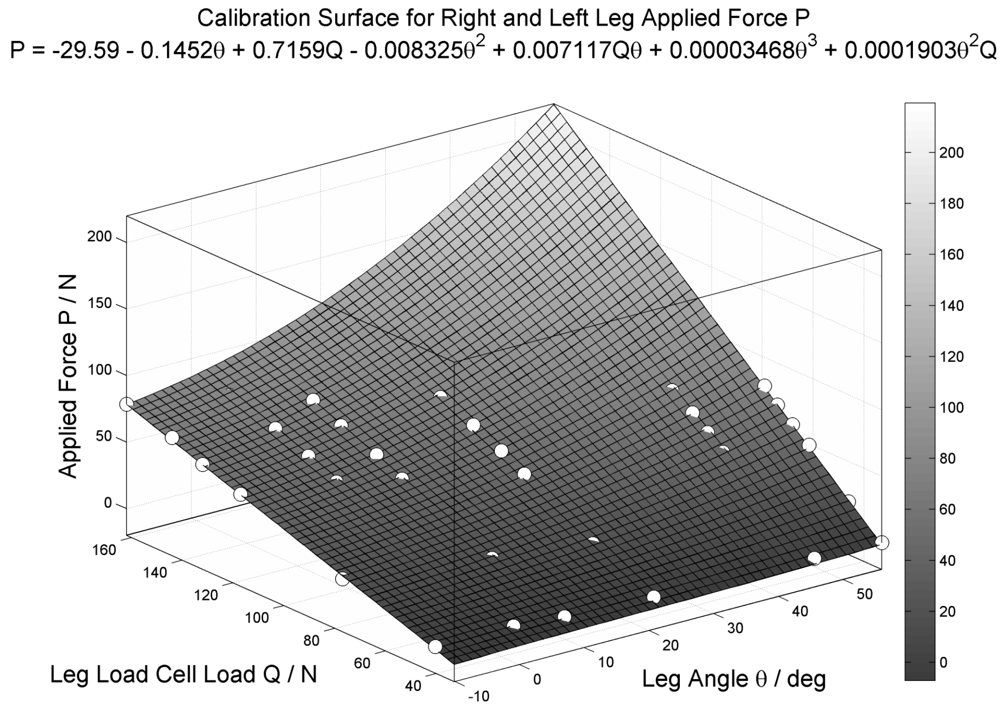


Figure B-5: A graph of hysteresis in the load and angle of the left leg support. This is the reason the seat movements and force measurements were calibrated with a three dimensional surface, because the applied torque $T = f(Q, \theta)$. The hysteresis introduces a substantial variation in the angle for a given force.



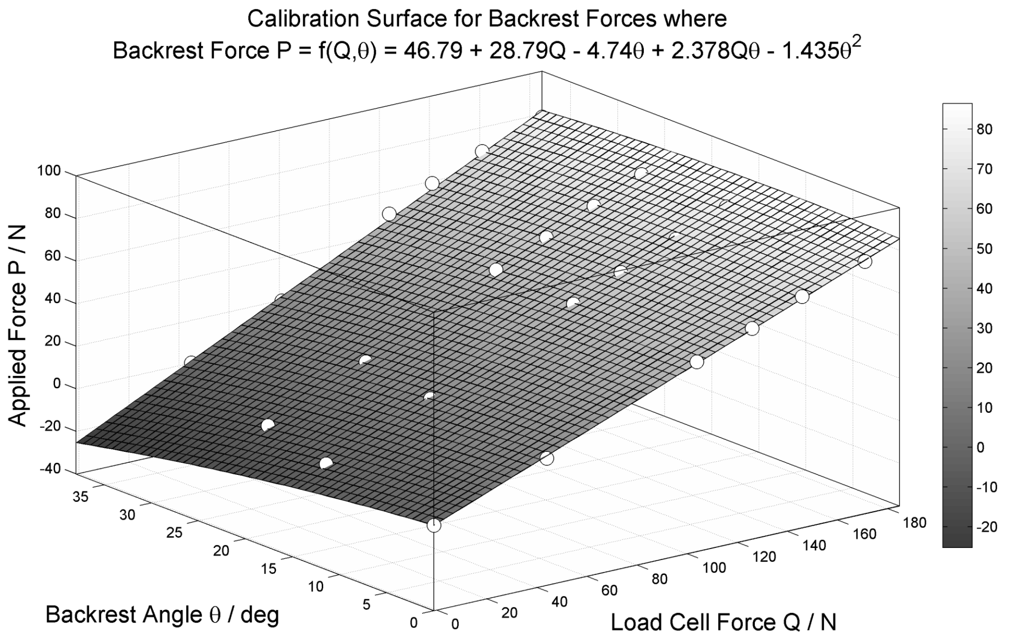


Figure B-6: Two calibration surfaces derived from measured data for the leg support and backrest forces. These graphs are for a backrest force applied at radius R = 0.337m and a leg force applied at radius R = 0.176m. Both surfaces are linear for Q, the measured load cell force; but polynomial for θ, the angular position.

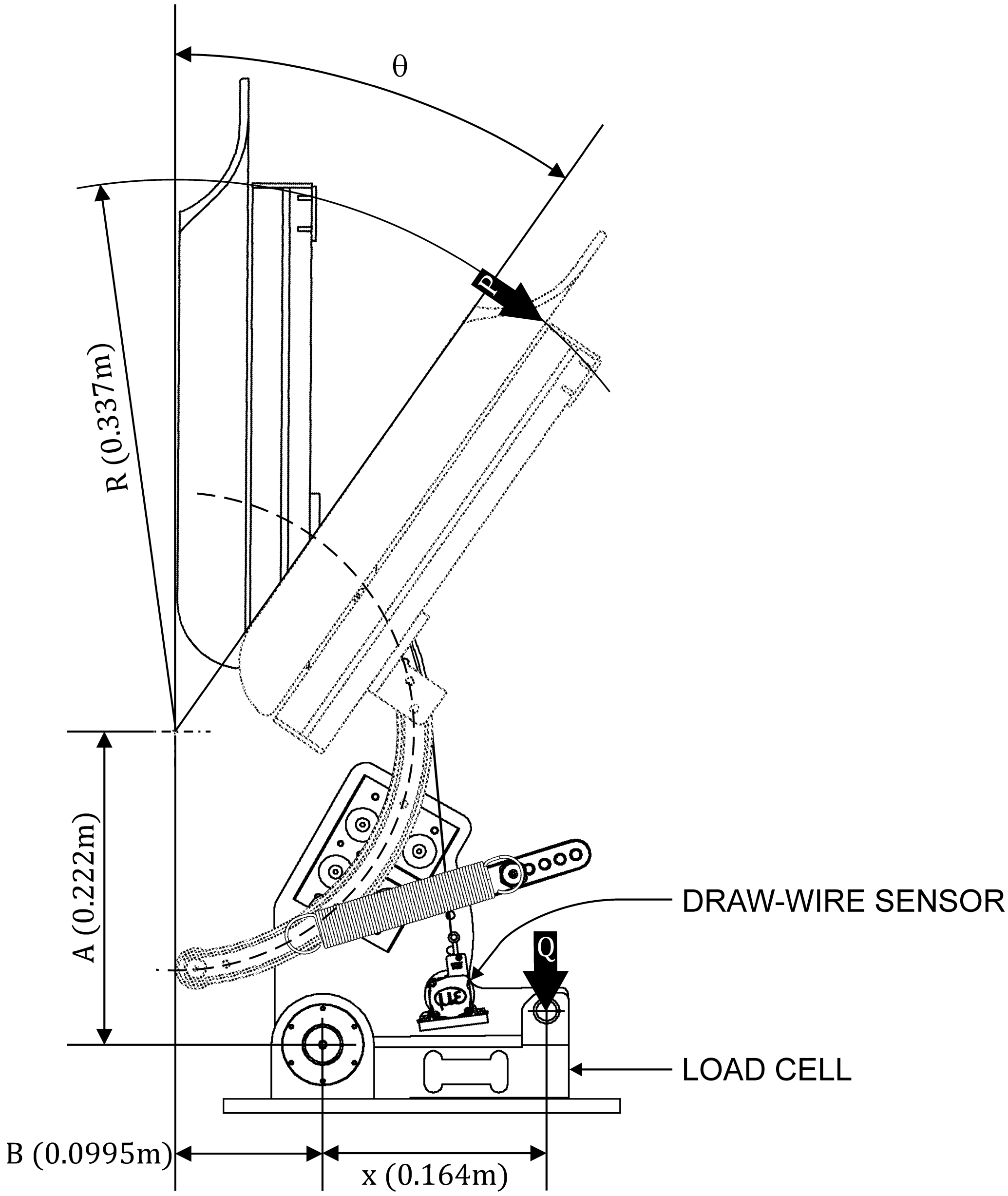


Figure B-7: A diagram of the dimensions (A, B, x, R, θ) relating the backrest load cell force Q to the applied backrest force P.

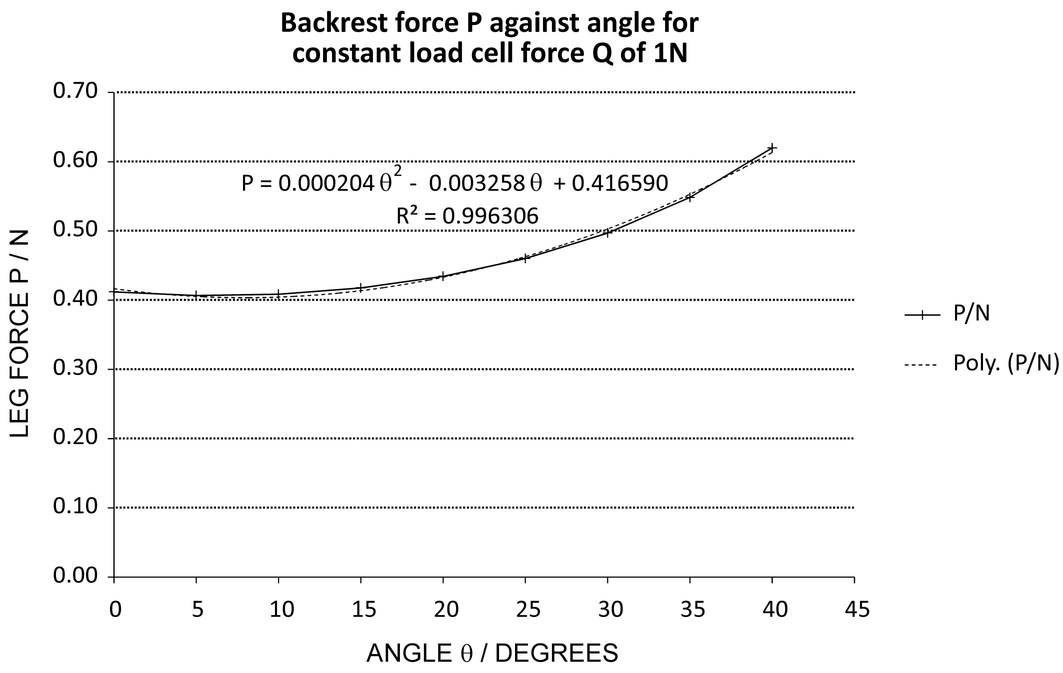


Figure B-8: A plot of Equation B.5 for force P against leg support angle θ, for a constant load cell force Q of 1N.

$$P_{backrest,R=0.337m} = f(Q,\theta) = 0.5743 + 0.4588Q - 0.3885\theta + 0.003028Q\theta - 0.00721\theta^2 \quad \text{(B.6)}$$

The derived surface is shown with the leg surface in Figure B-6.
This equation provides applied forces (P) at 0.337m radius from the backrest centre of rotation.
Torques are calculated by multiplying the applied force P by the radius R.

B.4 Error estimation

The errors in the system have been identified, estimated and combined using the Root Mean Square method.

B.4.1 Angles

The angle measurements for the hips and backrest were measured with hiqh quality sensors and simple direct linear mechanisms.

Leg Angle

Leg Angle θ was measured with a precision multi-turn potentiometer which turned through a pair of gears (ratio 24:80) with the spring drum. The seat used 83% of the full range of the potentiometer.

Error Type	Parameter affected	Angle Error, θ
Potentiometer tolerance ($\pm 0.24\%$ operating range)	θ	$\pm 0.144°$
Protractor error during calibration	θ	$\pm 0.5°$
Data logger tolerance ($\pm 0.024\%$ operating range)	θ	$\pm 0.144°$
	RMS Error	$\pm 0.31°$

Backrest Angle

Backrest angle was measured directly and linearly with the draw-wire sensor running tangentially to the slides.

Error Source	Parameter affected	Angle Error, θ
Draw wire sensor tolerance(0.7% operating range)	θ	$\pm 0.42°$
Data logger tolerance (0.2% operating range)	θ	$\pm 0.12°$
Protractor error during calibration	θ	$\pm 0.5°$
	RMS Error	$\pm 0.38°$

B.4.2 Torques

The torque measurements were less straightforward due to the more complex measurement mechanism resulting in the measured torque being a function of the angle of the support and the applied torque. The errors from each of these components are combined and a Root Mean Square error calculated.

Backrest Torque

Calibration errors are given for worst case. Measurement system errors are as given by the sensor or 8 device manufacturer. Errors in the torque resulting from measurement error and sensor error were calculated using Equation B.6. See Table B.2 for a table of the backrest torque errors.
The two values for RMS error from Table B.2 yield an error equation where
$Error_{RMS} = f(TorqueT)$:

$$Error_{RMS} = \pm(0.037T - 0.014) \tag{B.7}$$

Leg Torque

Calibration errors are given for worst case. Measurement system errors are as quoted by the sensor or device manufacturer. Torque Errors are calculated using Equation B.3. The values for Q and θ are taken from maximum peak and unloaded points occurring in child data from 1/12/2012. See Table B.3 for a table of the leg support torque errors.
The two values for RMS error from Table B.3 yield an error equation where
$Error_{RMS} = f(TorqueT)$:

$$Error_{RMS} = \pm(0.034T + 0.18) \tag{B.8}$$

Table B.2: A table of torque errors for the backrest

BACKREST TORQUE ERRORS			
Error Type	**Parameter affected**	**Torque Error T = 31Nm**	**Torque Error T = 4.4Nm**
Radial positioning of load applicator during calibration ($\pm 1mm$ at 337mm: 0.3%)	R	$\pm 0.17N$	$\pm 0.024N$
Measurement of radius R during calibration ($\pm 3mm$ at 337mm: 0.9%)	R	$\pm 0.51N$	$\pm 0.072N$
Variation in angle of force applicator from perpendicular to support ($\pm 3°$: 1.4%)	Q	$\pm 0.85N$	$\pm 0.12N$
Variation in applied calibration load (reading error and tremor) ($\pm 2N$ at 19.62N: 10%)	Q	$\pm 6.1N$	$\pm 0.82N$
Load cell tolerance ($\pm 1.5\%$ operating range)	Q	$\pm 0.91N$	$\pm 0.12N$
Data logger tolerance ($\pm 0.03\%$ operating range)	Q	$\pm 0.018N$	$\pm 0.0025N$
Draw-wire sensor tolerance ($\pm 0.7\%$ operating range)	θ	$\pm 0.0016N$	$\pm 0.0002N$
Data logger tolerance ($\pm 0.2\%$ operating range)	θ	$\pm 0.0047N$	$0.0006N$
Protractor reading error ($\pm 0.5°$)	θ	$\pm 0.048N$	$\pm 0.048N$
Root Mean Square Error		$\pm$**2.07Nm**	$\pm$**0.28Nm**

Table B.3: A table of torque errors for the leg supports.

LEG TORQUE ERRORS			
Error Type	**Parameter affected**	**Torque Error, T = 33Nm**	**Torque Error, T = 1.4Nm**
Radial positioning of load applicator during calibration ($\pm 2mm$ at 176mm: 1.12%)	R	$\pm 0.20N$	$\pm 0.016N$
Measurement of radius R during calibration ($\pm 3mm$ at 176mm: 1.7%)	R	$\pm 0.30N$	$\pm 0.016N$
Variation in angle of force applicator from perpendicular to support ($\pm 3°$: 1.4%)	Q	$\pm 0.54N$	$\pm 0.094N$
Variation in applied calibration load (reading error and tremor) ($\pm 2N$ at 19.62N: 10%)	Q	$\pm 3.88N$	$\pm 0.67N$
Load cell tolerance ($\pm 1.5\%$ operating range)	Q	$\pm 0.58N$	$\pm 0.10N$
Data logger tolerance ($\pm 0.03\%$ operating range)	Q	$\pm 0.012N$	$\pm 0.002N$
Potentiometer tolerance ($\pm 0.24\%$ operating range)	θ	$\pm 0.0011N$	$\pm 0.0003N$
Data logger tolerance ($\pm 0.024\%$ operating range)	θ	$\pm 0.0011N$	$0.0000N$
Protractor reading error ($\pm 0.5°$)	θ	$\pm 0.24N$	$\pm 0.021N$
Root Mean Square Error		$\pm$**1.33Nm**	$\pm$**0.23Nm**

B.5 Determining Spring Settings

A simple calibration procedure was carried out after the long-term evaluation to determine the modified spring settings used with A1's evaluation of the seat in October/November 2011. A simple force applicator was built using a large compression spring. This was calibrated using a high quality scientific digital balance where its was calibration checked with standard masses. A sketch of the applicator is shown in Figure B-9. The applicator was used to apply known forces to the hip joints and backrest, and the displacements and sensor outputs were recorded. Angles were measured during this calibration with a protractor, and were consistent to $\pm 0.5°$.
The spring rates and movement thresholds for the hip joints and backrest were calculated using a linear regression from the calibration data as below:

Joint	Spring Rate (Nm/deg)	Torque Movement Threshold (Nm)
Backrest	1.28	3.66
Left Hip	0.4	3.47
Right Hip	0.29	5.8

The spring rates were set or modified by initially winding the constant tension springs fourteen turns. They were not calibrated prior to installation in the seat, as they were likely to be (and were) adjusted at the child's school where such calibration facilities were not available, and time for such a procedure was short. It was assumed that each spring, which was manufactured to the same process and specification, would have an identical characteristic.

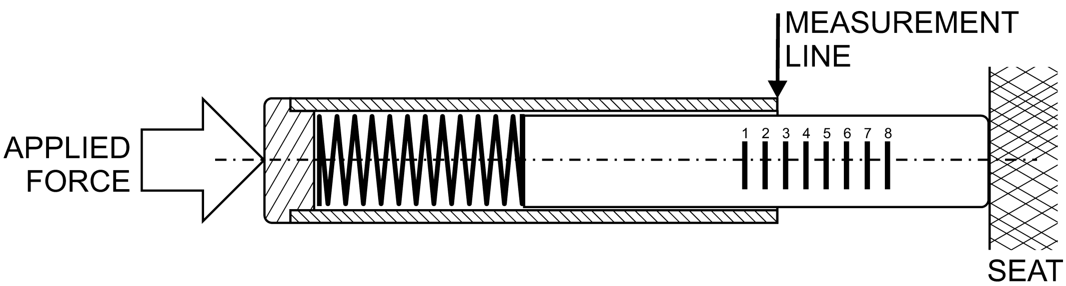


Figure B-9: A drawing of the calibration tool used to determine the relationship between the applied and measured seat forces. As the applied force increases, the spring compresses and the end of the tube moves down the scale. The applied force is read from the position of the end of the tube on the scale. This sensor was calibrated with a digital balance.

Appendix C

Large data set from A1 1/12/2011

These six graphs show the entire data set for the morning of 1-12-2011 where A1 evaluated the second independent seat. The graphs show the backrest torque and angle in parallel plots.

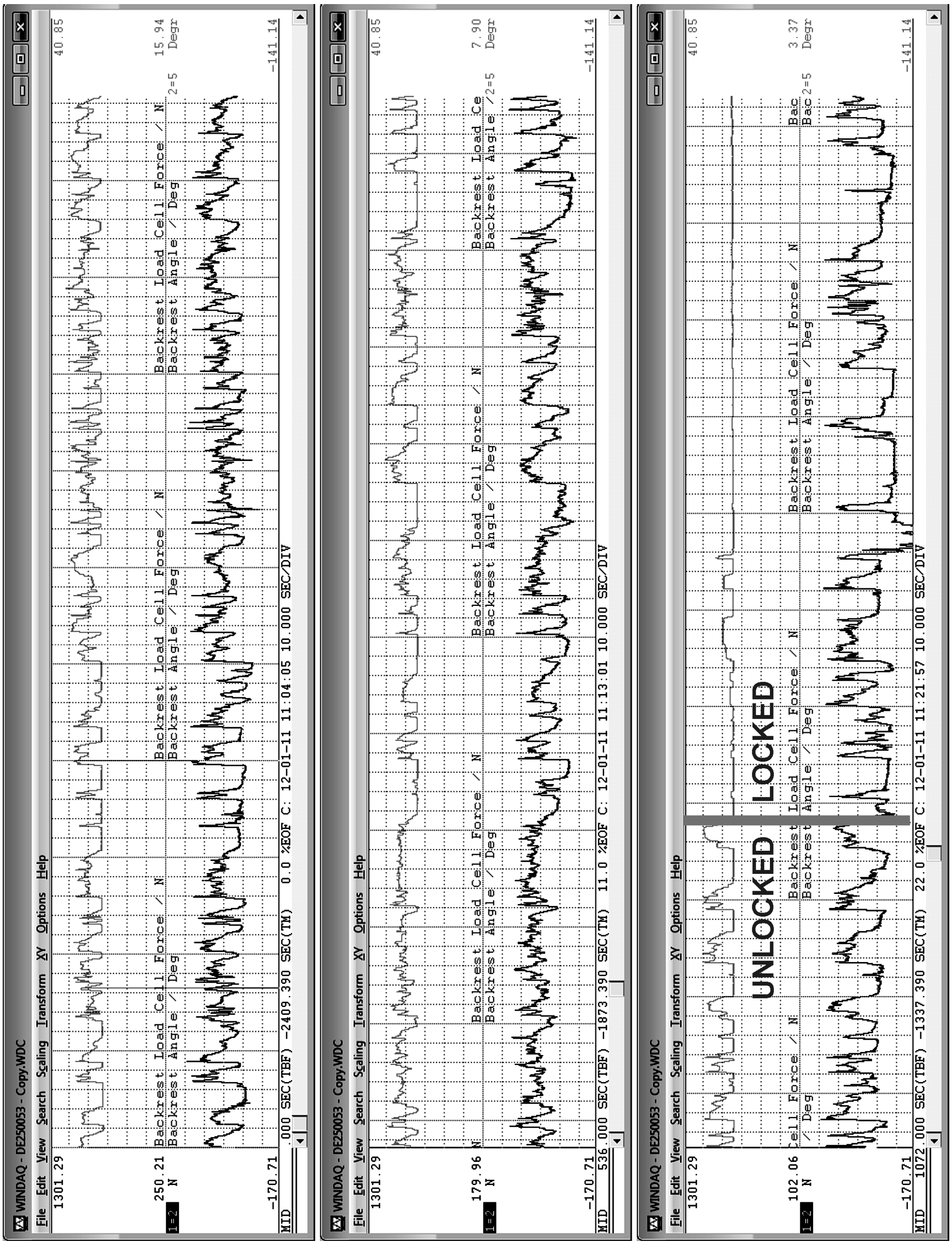


Figure C-1: These three graphs show the first half of the entire data set for the morning of 1-12-2011 where A1 evaluated the second independent seat. The graphs show the backrest load-cell force and angle in parallel plots.

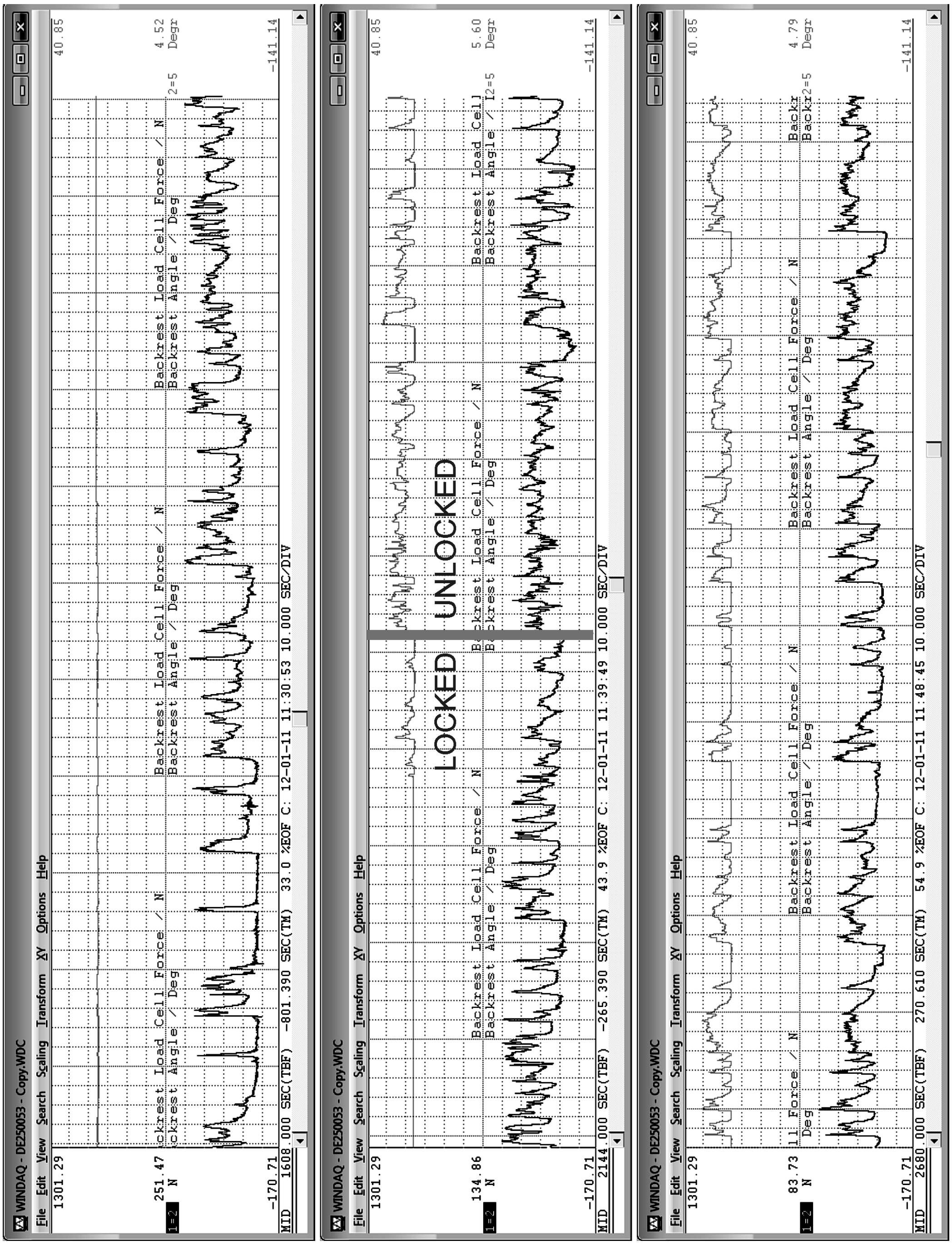


Figure C-2: These three graphs show second half of the entire data set for the morning of 1-12-2011 where A1 evaluated the second independent seat. The graphs show the backrest load-cell force and angle in parallel plots.

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